CLEAN ENERGY FOR GREEN BUILDINGS: AN OVERVIEW OF ON- AND OFF-SITE ALTERNATIVES

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INTRODUCTION

There are many reasons to pursue clean energy alternatives in both new-built and renovated/upgraded buildings. The most obvious is, of course, the direct economic benefit of either reducing ongoing energy costs by using fuel and electricity more efficiently, or by eliminating these costs entirely when incorporating renewable energy sources such as solar or wind power.

However, there are other benefits as well. In some cases, the building owner may be required by law to use greener sources of energy in order to help protect the environment, for example by reducing air pollution. In other cases, the building's owner may wish to incorporate clean power in order to promote a green image to the residents or occupants of the building (in the case of an office building or residential complex) or visitors to the building (such as shoppers in a retail facility).

In this paper, we take a broad view of the clean energy decision. Instead of asking, "how can builders install solar or wind in their facilities?", we want to know, "how can builders best achieve the goals that clean energy can deliver?" We see three options that can help to answer this broader question, namely on-site renewable energy, on-site energy efficiency, and off-site clean energy. As we go through these options in this paper, we will be answering questions such as:

- *What background about the energy scene does the green builder need in order to make an informed decision about clean energy?*
- *What are some of the obstacles and opportunities that arise when incorporating on-site clean energy technologies?*
- *What are some of the pros and cons of on-site versus off-site clean energy options?*

The focus of the paper is mainly on options for electricity supply, but some of the points raised are applicable to heating and hot water energy supply as well.

BACKGROUND: REMIND ME AGAIN WHY CLEAN ENERGY IS A GOOD IDEA?

Although the answer to this question may seem obvious to any builder in the green building field, it is useful to summarize the arguments in favor of clean energy, as background for the case studies and discussion that come later in this article. (In the rest of this article, we will refer to the person having responsibility for decisions about clean energy for a green new build or retrofit as "the builder.")

As a starting point, we define "clean energy" as an energy source that reduces or eliminates pollution and greenhouse gases by using renewable energy or through the efficient use of fuels such as natural gas that can be combusted more cleanly. We can look at the mix of sources of electricity when a building owner buys electricity from the grid to consider whether the energy in use already constitutes clean energy. Figures 1a and 1b show the breakdown of electric production by source for the United States as a whole and for New York State, respectively. These figures are for "commercial" electric production, which is the vast majority of the electricity generated; in addition, electricity produced in industry for internal on-site use, or by residences for on-site or off-the-grid use, is not included.

Looking at the national average, it is clear that while nuclear and hydropower contribute substantial amounts to the national total, the majority of electricity is generated from fossil fuels, with coal alone

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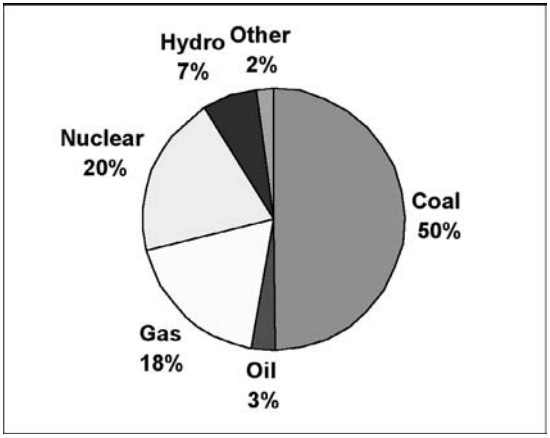
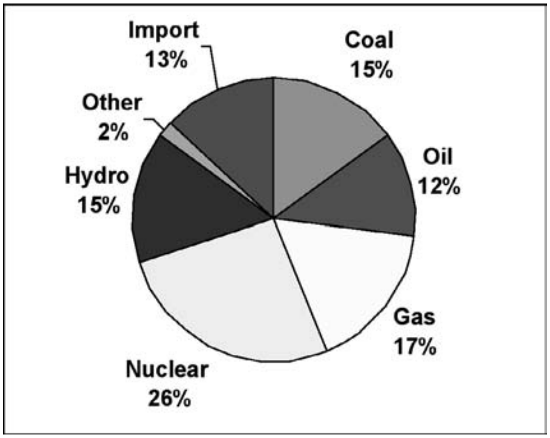
FIGURE 1. Breakdown of electricity production by source for (left) USA and (right) New York State, 2004. Total amount is 3,971 billion kWh for USA, 158 billion kWh for NYS. "Other" category includes a mixture of renewable and non-renewable sources such as wind, trash-to-energy, etc. For NYS, "Imports" category includes net imports of electricity from neighboring states and Canada, whose energy source is unknown. Data sources: US Energy Information Agency (2006), for USA; NYSERDA (2005), for NYS.





accounting for 50%. The example of New York State shows that state-specific breakdowns can vary quite a bit from the national average. For the NYS market, hydro, nuclear, and gas account for 58% of the total, which helps to reduce certain emissions per kWh compared to the average values for electricity from coal. For readers from other countries, it generally holds in many parts of the world that 50% or more of the electricity comes from fossil fuels, but there are exceptions, such as France with 79% of electricity generated from nuclear (Rhodes and Beller 2000). The bottom line is that, since for the most part the grid relies on fossil fuels, clean energy options can help move a building away from the use of non-renewable resources. As of 2004, renewable sources other than hydro accounted for only 2% of the total electricity generated in the US, so there is plenty of room for growth.

It is striking that in Figure 1a, among the three fossil fuels included, coal has the largest share of electric production from fossil fuels, while oil has only a very small share. Table 1 shows how coal is also the one fossil fuel that the US possesses in abundance, relative to the amount of annual consumption. The numbers in the first column are the proven reserves for each energy source, and at first glance it might seem that in 10 years or so, domestic supplies of oil and gas will be completely exhausted! What is more likely to happen is that the energy industry will continue to find resources, and also new imports may be brought in from fossil-fuel rich regions such as Russia and the Middle East, so that the final depletion of the known US resources will be postponed. Eventually, though, we won't be able to make up for dwindling known reserves with new discoveries or increased imports, and the total availability and output of oil and gas from conventional sources around the world will go into a permanent decline. That is what has already happened to the domestic US oil industry: its current output of 2.1 billion barrels in 2003 is down from a peak of 3.5 billion in the early 1970s.

Next, we cannot talk about the question of energy without bringing up the question of pollution. The

TABLE 1. Domestic reserves and annual production of fossil fuels in USA, 2003.

	Units	Reserve	Production
Oil	Billion barrels	21.9	2.07
Gas	Trillion cubic feet	189.0	21.6
Coal	Million tons	492.0	1.02

Source: National Mining Association (2005), for coal data; Energy Information Agency, US Dept of Energy (2005), for all other data.

US electric power industry has done a reasonably good job—though not a perfect one—of eliminating air pollutants such as NO_x and SO_2 at the smokestack. This leaves the major concern of today, namely the greenhouse gas CO_2. Unfortunately, the fossil fuel that we have the most of is also the one that emits the most CO_2 per unit of energy released. To illustrate this point, here are the three chemical reactions governing the combustion of coal, gas, and oil*:

Coal: $C + O_2 > CO_2 + 30$ MJ/kgC

Gas: $CH_4 + 2O_2 > CO_2 + 2H_2O + 50$ MJ/kgC

Oil: $C_{12}H_{26} + 18.5O_2 > 12CO_2 + 13H_2O + 50$ MJ/kgC

The amount of CO_2 released per unit of energy provided can be calculated from these reactions by comparing the molecular mass of fuel going into the reaction to the mass of CO_2 emitted. For example, the molecular mass of an atom of carbon is 12, that of oxygen is 16, and that of hydrogen is 1. Taking the simple case of combustion of coal, the mass of the coal atom is 12, and the mass of the CO_2 atom is 44, so the amount of energy released per unit of CO_2 emitted to the atmosphere is 30 MJ/kgC × (12/44) = 8.18 MJ/kg CO_2. Repeating this exercise for gas and oil gives 18.2 MJ/kg CO_2 and 16.1 MJ/kg CO_2, respectively—a significant advantage for gas or oil over coal.

The upshot of this comparison is that for purposes of preventing climate change, it is good to have carbon-hydrogen bonds in the fuel that you are combusting. Coal does not have any, so it has the lowest amount of energy released per unit of CO_2 emitted to the atmosphere. This is a problem, because fully 39% of CO_2 emissions in the USA in 2004 came from electricity generation, and of these, approximately four-fifths were from coal-fired generation. The best hope for coal is *carbon sequestration*, a process to separate the CO_2 byproduct from the waste stream and capture it underground or put it to some other use, rather than allowing it to go up into the atmosphere. Pilot projects demonstrating sequestration are already under way. Since 2001, the Great Plains Synfuels Plant in the state of North Dakota has separated out CO_2, which is pumped via pipeline to Canada and then injected into a gas field, where it is sequestered and at the same time helps to extract additional natural gas, a process known as "enhanced recovery" (Dakota Gas Plant 2006). Although a mature sequestration technology is still years if not decades away, coal sequestration plants might someday create both electricity for the grid and hydrogen for transportation, while eliminating all air pollutant and greenhouse gas emissions to the atmosphere.

The Renewable Alternative

Turning to alternatives to fossil fuels, the large-scale production of electricity from renewable resources, especially from wind, has really taken off in the last few years. Taking the wind example, the American Wind Energy Association (2006) states that in August 2006, wind power installations reached 10,000 MW of installed capacity; at that point, the market was on track to install 3,000 MW in all of 2006, which is more than the entire capacity installed up to the year 2000 (2,500 MW). This growth in large-scale wind has also benefited makers of small turbines, who are producing a greater range of models in larger quantities than ever before. Solar photovoltaics and other renewable energy technologies are also expanding rapidly.

The Effect of Energy Prices

Looking to the future, there are a number of trends that may affect the price of electricity either upward or downward, and possibly also the attractiveness of clean energy options for buildings. On the one, coal is plentiful, and a new generation of more efficient coal-fired plants may be in the works, that might actually bring prices of conventional electricity down somewhat. The US Dept. of Energy recently predicted a slight *decline* of about 8% in wholesale average cost of electricity, in real terms, for the period from 2003 to 2033 (Stecky 2004). On the other hand, the continuing challenge to find new sources of oil and gas to satisfy growing demand suggests that prices are likely to go up over the next 5 to 10 years. Furthermore, there may be legislation to curb greenhouse gas emissions that could increase the cost of electricity. Currently, electricity from clean sources

* Energy content value given for coal is for high-quality, relatively pure coal. Coal with a high moisture content or with significant impurities has lower energy content per kilogram. For oil, the formula for kerosene, a.k.a. #1 diesel, is used as a representative petroleum product that can be combusted in a power plant to make electricity.

such as wind or biofuels in most cases costs more, if one takes into account only the direct economic purchase cost. The smaller the difference between conventional and clean power, the easier it is for building owners to commit to it.

So far we have looked at the arguments in favor of clean energy in general, including moving away from nonrenewable resources and avoiding CO_2 emissions. Next we focus on "on-site" systems that are physically in the same location as the building, in contrast to "off-site" systems, such as commercial wind farms. Among the clean energy options available, on-site production of energy is increasing in popularity in many states across the United States as well as in many foreign countries, such as Germany and Japan. For example, in the state of California alone, residents installed 180 MW of PV systems on the roofs of their homes, businesses, government, and schools between 1996 and 2006 (Go Solar California 2006). In the next section we will look at some examples of on-site clean energy installations.

EXAMPLES OF ON-SITE CLEAN ENERGY SYSTEMS

In this section we consider three examples of on-site clean energy systems. The first two are renewable systems, namely a small wind turbine and a photovoltaic system; the last one is a small-scale cogeneration system that provides both electricity and hot water from natural gas, as a contrast to the renewable energy system. For each example, we describe the technology, and then discuss its performance as an investment and any practical considerations involved with making an installation. We use simple payback throughout, on the grounds that 0% financing is a way to take into account the environmental benefits of clean energy. Note that this assumption will noticeably affect the economics of a project, especially where the payback is over a period of many years. In situations where the builder pays interest on loans used to purchase energy equipment, their effect on the payback period must be taken into account. Also, all sites are assumed to be on the electric and natural gas grids; for remote sites, the builder can trade off the additional cost of batteries and backup power sources (e.g., diesel generators), versus the cost of bringing in grid power to the site (but those options are not discussed here).

Example 1: Small-Scale Wind Energy

First, a quick and basic review of what a wind power system is. The heart of the system is the wind turbine, which consists of a "hub" with attached turbine "blades" (typically three of them) that rotate around the axle that passes through the hub. A generator inside the hub converts the rotational energy of the axis into electrical energy, and then electronic controls either in the hub or on the ground modify the electrical current so that it is compatible with electricity from the grid. The turbine must be able to rotate to catch the wind from whatever direction it is coming, and in addition to allowing rotation of the hub, the "tower" must be strong enough to support the turbine in high winds and tall enough to catch sufficient wind, since average wind speed increases with height. A freestanding turbine tower for a small turbine is ideally erected (with or without guy wires) in a cleared area without many trees or buildings nearby, and can be anywhere between 40 and 120 feet high. A minimum height of 80 feet is recommended. When space is more constrained, smaller turbines can also be attached directly to a building on a shorter tower.

Wind turbines are measured in terms of their rated capacity, with turbines of 50 kW and under considered to be small turbines, while those with 500 kW or more of capacity considered to be large or utility-scale turbines; currently there are no products in the range in between 50 and 500 kW in the US market. Rated capacity is not the true output of the turbine; rather it is the output at the rated wind speed, which is usually quite high (a typical rated wind speed is 25 MPH). Average wind speeds are lower than the rated wind speed, so the actual output from the wind system is likely to be a good bit lower than what you would get at the rated wind speed. For example, take a small-sized turbine rated at 10 kW at 25 MPH wind. If the wind blew 24/7 at that speed you would get

10 kW × 8,760 hrs/yr = 87,600 kWh per year of electricity

Now we can introduce the *capacity factor*, which is defined as

Capacity factor = actual annual output/annual output at rated capacity

PHOTO 1. 10-kw wind turbine near Ithaca, NY, in summer. Turbine is mounted on 80′ tower, which is held in place on three sides with guy wires. (Courtesy of Michael Miles.)

PHOTO 1A. 10-kW wind turbine near Ithaca, NY, in winter. Turbine is mounted on 80′ tower, which is held in place on three sides with guy wires. Photograph was taken at around 3 P.M. on January 28, 2007. In a light breeze, rotations were fluctuating around 70 RPM and the output was around 0.5 kW. (Photograph from author's own collection.)

So if the capacity factor based on local wind conditions were 33% (a very good site for wind), the above device would produce 28,900 kWh, and not 87,600.

Turbines have a "cut-in" wind speed below which there is not enough energy in the wind, so that they do not generate electricity at all. Above the rated wind speed, the output from the turbine will hold constant or even decline, even though the amount of energy in the wind increases. This feature is incorporated in order to protect the turbine from excessive stress forces that might otherwise damage it. Some turbines also have a shutdown or "cut-out" wind speed, usually quite a bit larger than the rated wind speed, above which the turbine will stop entirely. All turbines are equipped with a mechanism for halting rotation for reasons of maintenance or emergency conditions.

Estimating Power Available from Wind. Estimating the power available from the wind is not as simple as taking the average wind speed and calculating the power that would be available if the wind blew continuously at this speed all year long. It is worthwhile for anyone considering wind power to understand the relationship between the distribution of wind speeds and output from the turbine, so we will spend some time on this question. Calculations of wind power are described in more detail in Vanek (forthcoming).

Assume for example we have a site where the average windspeed is known to be 12.8 MPH (5.7 meters/sec.) at a given height above the ground, to which the proposed turbine tower is to be built. (This height is also known as the "hub height.") The average windspeed value might be obtained from a simple wind map of the region, or it might be obtained more carefully by gathering windspeed data at the site continuously for one year or more, and calculating an exact average.

Next, it is important to know that the amount of power available in the wind grows with the cube root of the wind speed. In other words, at high wind speeds, there is MUCH more power available in the wind. We can calculate the power available per unit of "swept area," or the cross-sectional area covered by the rotation of the blades of the wind turbine* as

$$\text{Power} = 0.5 * \text{Air Density} * (\text{Windspeed})^3$$

* For example, a turbine with 10-foot long blades has a swept area $A = \pi * R^2 = \pi * 10^2 = \sim 314 \text{ ft}^2$.

where air density is on the order of 0.065 lb/ft^3, or 1 kg/meter^3 in metric units. So, if we double the windspeed from the average value of 12.8 MPH at this site to 25.6 MPH, there is eight times as much power in the wind.

Suppose we only know the average windspeed at a site and do not have the means or the time to gather data for a year. From past observations and experience, those interested in wind power have found that in many locations, the pattern of wind speeds follows a distribution called a "Rayleigh Distribution" from statistics, which can be generated if we know the average speed. The distribution has the following form:

Probability (Windspeed ″ v) = $1 - \exp[(-\pi/4)(v/v_{average})^2]$

where v is the target windspeed, $v_{average}$ is the average speed (12.8 MPH in this case), and exp is the exponential function. So, for example, if you put the value 0 MPH into the equation, the probability will be 0%; if you put a very large number like 300 MPH in, the value will be 100. Also, to calculate the Rayleigh estimate for the probability that the windspeed will be between two values, we calculate the percent value for the higher value and then subtract the percentage for the lower value. For example, the probability that 8.1 MPH < windspeed < 10.4 MPH is P(windspeed < 10.4 MPH) = 40.7% minus P(windspeed < 8.1 MPH) = 27.1%, or 40.7% – 27.1% = 13.6%.

To show how well the estimate using an average windspeed value and the Rayleigh distribution can fit an actual site, we can plot the estimated curve on top of measured wind data from an actual site that has the same average wind speed of 12.8 MPH, as shown in Figure 2. In this graph, possible windspeed values from 0 up to 37 MPH are divided into windspeed "bins," with bin 1 having a speed of 0 MPH (i.e., times with no wind), and then bin 1 averages 1.2 MPH, bin 2 averages 3.5 MPH, and increasing average windspeed by 2.3 MPH in each successive bin up to bin 17 with average speed 35.9 MPH. The percent probability for each bin is then plotted, using the percent of hours per year for the "actual" curve and the Rayleigh distribution for the "estimated" curve. For example, for Bin 2 in Figure 2, the actual curve gives 2.3% of hours per year, or 204 hours, having an average windspeed in this bin range, while the estimated curve gives 2.5% or 219 hours. As shown, the Rayleigh distribution fits the actual data fairly well, so an estimate of the annual energy output using this estimate would give a reasonably good value for projecting the performance of the turbine at the site. The average speed of 12.8 MPH falls in bin 7. Notice that for a significant number of hours of the year, the average windspeed will be well above this value (e.g., 15–18% of the hours in bins 10 to 12), and these higher winds boost the overall amount of wind energy available compared to the energy from wind blowing 12.8 MPH continuously year-round.

Economics of Applying a Turbine Technology to a Site. Once the energy available in the wind is known or estimated, the output of the turbine for a year can be projected based on the performance specifications of the turbine. Turbines have varying rates of conver-

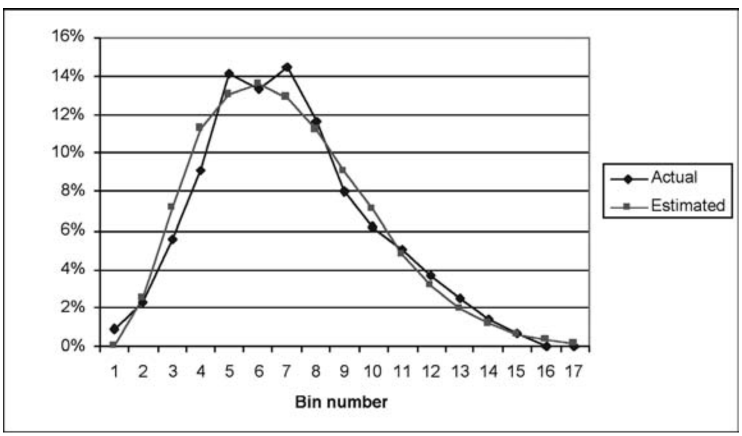


FIGURE 2. Measured and estimated wind distribution curves with average wind speed of 12.8 MPH.

sion efficiency at different wind speeds. There are many different turbine designs, and we won't give the specific numbers for each design here. However, they all have in common that below the cut-in wind speed, they obviously have 0% conversion efficiency, then they start at a low efficiency value above the cut-in speed, increase to some maximum efficiency value at the ideal operating windspeed for the turbine, and then decrease in efficiency as the windspeed increases to the rated windspeed and beyond—this is the "power curve" for the device. If the builder knows the average speed for each of a number of bins, the number of hours per year that the wind is expected to blow in that bin, and the conversion efficiency of the specific turbine proposed for the site, she or he can estimate the total output of electricity for the year.

Continuing with our example of a site with 12.8 MPH wind, a 10 kW turbine with a typical power curve might see a capacity factor of 25% with this wind resource, so the actual output per year would be about 22,300 kWh. Assuming the electricity generated displaces energy from the grid, and a retail rate of $ 0.13/kWh, the output is worth $2,895 per year. The retail cost of the installation including turbine, tower, connection, and all labor might be between $45,000 and $65,000, so the simple payback would be between 16 and 22 years. Rebates of up to 50% are available to home and business owners in some states, and these are clearly advantageous, since a 50% rebate would bring the payback period for this example down to between 8 to11 years. We reiterate that the economics are highly sensitive to the available wind resource; even at 8 or 10 MPH average wind the representative 10 kW turbine system above becomes much less economical.

Practical Considerations. Unlike solar energy, which usually falls more or less evenly in the same city or county, wind energy is very location specific. The average windspeed at a given tower height on top of a hill or ridge can be quite different from the windspeed in a valley just a few miles away. Therefore, it is very important to understand the effects of local terrain, and if different sites are available adjacent to a building, to choose the optimal one.

Once it has been measured in a specific location, the wind resource is also quite consistent from year to year. If the builder makes the effort to gather data for an entire year and calculate average windspeed and bin frequency, the distribution of wind in subsequent years will usually not change more than 10% up or down. This is very helpful, since one can invest in wind knowing that there will not in the future come a "bad" year in which the air is still most of the year and the turbine output drops off by 50% or more.

At the outset of the project, the builder faces a question about how much to invest in wind data gathering. One option is to install an anemometer on a tower at the proposed "hub height" of the turbine, which may add several thousand dollars to the total project cost, but will allow the accurate prediction of the economic value of the turbine. The builder can also forego the data measurement and use an estimated average wind speed from meteorological data or a *statistical wind map* as a basis for deciding to invest in wind, but this route involves a risk that the project may not be as cost-effective if the actual average wind speed and distribution turns out to be less favorable than the prediction.

Lastly, the availability of "net metering" is very important for wind power. It is very beneficial to get monetary credit at the retail rate per kWh for excess turbine output that is sent onto the grid. For example, a winter weather system with strong winds may allow the turbine to generate many kWh of electricity over a 24- or 36-hour period that are not used by a homeowner because household electric demand is low (the a/c is off, and furthermore indoor temperatures are cool, so the refrigerator is not drawing much power). If the turbine is forced to "dump" this excess power onto the grid without gaining any economic benefit via net metering, the economics of the whole system are greatly diminished.

Example 2: Home- or Business-sized Photovoltaic System

Compared to the wind system in the previous example, estimating the output of the photovoltaic (PV) system is somewhat simpler, so the economic analysis is more transparent. The system consists of an "array" of PV panels (also known as "modules"), each of which is typically rated at between 100 and 150 watts of output in full sun. (We won't go into the physics of how the panel converts sunlight to elec-

PHOTO 2. Installing a PV array in Malden, MA. In this case, the supporting rack is first attached to the roof, and then the panels are attached to the rack. In other designs, the panels and racks are assembled into a unit on the ground and then lifted into place, or some panels lie flat on the roof without any use of a rack. (Courtesy of Paul Lyons, Zapotec Energy, Cambridge, MA.)

PHOTO 3. PV system with elevated rack in Ithaca, NY. Here the builder has chosen to elevate the rack angle above the pitch of the roof, incurring extra cost but also achieving an angle more ideal for the location. (Photo from author's own collection.)

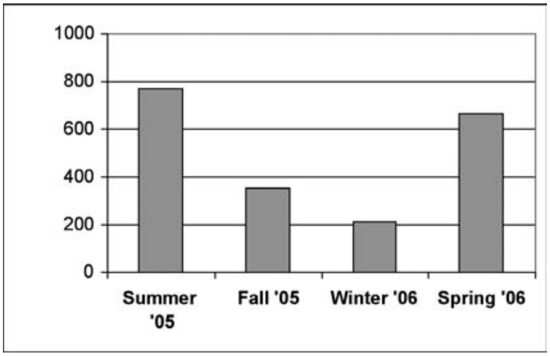
tricity here; see, for example, Stone, 1993, or Corkish and Prasad 2006.) Adding more panels to the array increases the system size. In this example, I will focus on an actual array of 16 panels in Ithaca, NY (42 deg. N Lat.), each rated at 140 watts, for a system size of 2240 watts. Other components of the system include the rack for mounting the panels, either to the roof or to a stand-alone structure at ground level, and an inverter to convert DC current from the panels into AC current for household use.

Some variations in the components of the array are possible. A stand-alone system can be mounted on a "tracking" panel that follows the sun as it moves across the sky; depending on local factors, the additional output from the array may offset the extra cost of the tracking system. Also, new products such as panels that incorporate the conversion to AC into the panel (so that one does not need an inverter) or roof shingles that incorporate the photovoltaics (more aesthetically pleasing, since the rooftop rack of panels is no longer a separate entity). As of this writing, the DC rack-mounted panels are generally more cost-effective than these other two options, but the latter are declining in cost, so the prospective buyer of a PV system should compare prices at the time of choosing a PV option.

The actual output of a fixed-position array depends on many factors, including the angle of the array relative to horizontal, the degree to which the array is angled either east or west of due south, whether the array is in shade at any time of day, and most importantly the prevailing climactic conditions. The Ithaca array is on a south-facing roof with approximately a 25-degree angle; the roof also faces roughly 15 degrees west from south. Also, the Upstate New York region in which it is located has a fair, though not excellent, solar resource. According to the National Renewable Energy Laboratory (NREL), the region averages 4,000 watt-hours of energy per square meter per day year-round, versus 6,000 wh/m^2 for the San Diego area (NREL 2006). The output for one year of system function from mid-June 2005 to mid-June 2006 is shown in Figure 3. The spring '06 block is from March 21 to June 20, and the summer '05 block is from June 21 to September 20, so as might be expected, the sun is both striking the array for more hours per day and also higher in the sky and therefore at a more favorable angle. Thus the output for each of these two blocks is around 700 kWh, versus around 300 kWh for the fall and winter blocks shown.

Economics of the Solar PV System. The cost of the system before and after incentives is shown in Table

FIGURE 3. Output from 2240 watt solar PV array by season in Ithaca, NY, Summer 2005 to Spring 2006. (Source: authors' own data gathering.)



2. Most of the cost of the system (70%) is the purchase cost of the panels, and in general, material costs dominate labor costs in PV system installations. The inverter must be sized to have a large enough maximum capacity to accept the maximum output from the array, and larger inverters on larger arrays will cost more. From above, the total annual output per year for 2005–06 was approximately 2000 kWh, so if this amount proved to be the long-term average output from the system, it would generate electricity worth $260 per year at $0.13 per kWh. At $5,760 net cost after incentives, the system would take 22 years to pay for itself—this may be longer than some customers may be willing to wait! However, recall that the relatively low average solar gain lengthens the payback period, in a sunny area such as the southwestern US, a 50% higher average rate of solar gain would decrease the payback period to 14 years.

There is an adage in the solar home business that "the first parts of the PV system that the customer should buy are the energy-efficient appliances that it will run." From a cost-effectiveness standpoint, this saying holds true, since it is cheaper to upgrade appliances to a more efficient level than to add extra panels to run less efficient appliances. For example, suppose a system like the one discussed above is installed on a newly-built 2000 square foot home. Since the home is not overly large, it might require 3,000 kWh per year with a family of four, gas dryer instead of electric, and middle-of-the-pack efficiency in other major appliances (refrigerator/dishwasher/washing machine). However, upgrading just these three appliances to high-efficiency Energy Star models, plus some additional compact fluorescent light bulbs, might trim the annual electric consumption to 2,000 kWh, all for a cost differential of $1,000 to $1,500. This is much less than the approximately $4,000 more it would cost, including labor and materials, to add enough additional capacity to generate the additional 1,000 kWh per year needed. In other words, it helps to see the PV array and the collection of lights, appliances, and other devices in the house as a "complete system," rather than making decisions about the size of the PV array in isolation from other decisions about the building.

TABLE 2. Cost breakdown for example 2240-watt PV array.

Panels	$10,500.00
Inverter	2,500.00
Balance of system	1,000.00
Labor	1,000.00
TOTAL	15,000.00
$3/watt NYS rebate	(6,720.00)
State income tax credit	(2,500.00)
Net cost	5,780.00

Source: author's own data gathering.
Notes: All costs shown include sales tax, where applicable. Balance of system includes racks for mounting panels, wiring to connect array to household wiring circuit, and all other miscellaneous small hardware. This system benefited from "sweat equity" contributions of the building owner, which kept the labor cost component low.

Other Practical Considerations. The time of year when solar PV systems make the most electricity is on hot sunny days in the middle of the day, when the sun is highest in the sky. This is also the time when the electric grid is under the greatest strain, due to air conditioning systems running at full power, etc., so PV systems help to dampen this peak in electricity demand, indirectly helping to reduce the threat of blackouts. Unfortunately, at the present time PV array owners do not get paid the peak value that is received by other larger producers in these maximum demand periods. If real-time demand pricing for electricity takes root in the US market, it is possible that in the future PV array owners would be paid in

PHOTO 4. PV system mounted at ground level near Ithaca, NY. Where space is not at a premium and a treeless field is available, as in this case, mounting on the ground facilitates seasonal adjustment of the rack angle and removal of snow. At 2:30 P.M. on January 28, 2007, snow has just been swept from the panels. Under overcast conditions, with the panels still somewhat blocked by snow, and at a low sun angle, output is around 180 W; prior to sweeping off snow, the system was producing 60 W. (Photo from author's own collection.)

real time what their excess output was worth, which might help the economics of investing in PV.

In addition, most grid-connected PV customers require grid access in order for their systems to operate, so if there is a blackout, the building owner cannot power her or his building with solar electricity until the grid is restored. Typical inverter designs for grid-tied PV operation require the AC oscillations coming from the line voltage as an input for synchronizing their output, so once grid power is lost, the inverter cannot function and the PV system goes down. Other inverter designs for stand-alone PV systems are not compatible with grid connection. Furthermore, in order to be able to operate the PV system as a back-up power supply during a grid power failure, one would need at least a limited bank of batteries and a means of dumping excess production, as both of these functions previously provided by the grid are no longer available. As long as loss of grid power is very infrequent, it may not be worth the trouble to design a PV system so that it can run independent of the grid. On the other hand, if the grid becomes less reliable in the future, retrofitting the necessary components may be viable, since most of the cost of the system is in the panels, which can be used in the retrofitted system without incurring any additional cost. Buildings in areas where grid reliability is currently an issue may be able to justify adding this equipment from the beginning.

Example 3: Small-scale Cogeneration (Cogen) System

Background Information. In this example we look at an energy-conservation technology that improves environmental performance by reducing the consumption of nonrenewable resources, rather than by replacing them with renewable resource use. The application is a large residential facility, in this case a multi-family apartment complex. The usual energy solution for these buildings is to heat domestic hot water (DHW) on-site with a gas-fired boiler and to purchase electricity from the grid. "Cogeneration," or cogen for short, means generating electricity and at the same time generating heat for some other application; it is also known as "combined heat and power" or CHP for short. In this alternative, a small-scale cogen system combusts natural gas to generate electricity; it then uses the waste heat from the combustion cycle to heat DHW, thereby extracting more useful work per unit of natural gas consumed. The actual technology at the heart of the cogen system can be either a small-scale gas turbine or a reciprocating engine, in either case coupled to a generator to convert mechanical energy from the rotating shaft to electrical energy.

Available Equipment Comparison

Microturbine vs. Reciprocating Engine. The expected efficiency of both main types is similar. Electrical generation efficiency generally is about 30%, and the thermal efficiency is about 50%. The reciprocating engine is a more mature technology, and is available in smaller sizes, down to 5kW. The minimum size for the microturbines is currently 30kW.

An additional technology in use for cogen is a Sterling engine version, which can use any source of heat. It is classed as an external combustion engine, because the working gas is not used up. One fascinating potential use being studied is to combust waste VOCs from an automobile painting plant, drastically

PHOTO 5. 375 kW cogen installation using five Tecogen reciprocating generator units in Waverley, NY. Piping loops (red) connect hot water byproduct to DHW, hydronic heaters, or absorption chillers. (Courtesy of Tecogen, Inc.)

reducing emissions and producing electricity and heat.

Fuel Usage. Microturbines utilize high pressure natural gas, up to 100 PSI; this is either included in the unit or required to be purchased separately. The energy to run the compressor is a parasitic load and decreases the overall efficiency of the unit. Included with fan and transformer losses, these can add from 5–13 kW of losses to the system. Emission losses, such as nitrous oxides from microturbines can be as little as 10% of the emissions of a standard reciprocating engine.

Reciprocating engines can utilize liquid or gaseous fuels. Sterling engines can utilize any type of heat that is of sufficient temperature to run the process.

Potential Markets. Microturbines and Sterling engines are able to use the relatively low methane percentage (as low as 30%) contained in Landfill Gases (LFG). There are a significant number of these installations already in place across the United States.

There are many building use types, such as medical facilities that are required to have standby power. For others, economically it is crucial that they maintain a continuous power supply, such as certain manufacturing plants. Many of these buildings currently employ a generator that is only used during power emergencies. They could instead utilize a CHP unit that can provide the backup capability needed, but also be saving them energy dollars on a continuous basis.

An advantage of providing local energy production is the reduction in the amount of energy required to be delivered around the country. Transmission of electricity is generally regarded as being a weak link in the chain of delivery to the consumer. Transmission and distribution losses are related to how heavily the system is loaded. U.S.-wide transmission and distribution losses were about 5% in 1970, and grew to 9.5% in 2001, due to heavier utilization and more frequent congestion. This elimination of transmission requirements both reduces the congestion of the system, and reduces the amount of power plant energy required, with a resultant reduction in pollution (USDOE 2006).

Some utilities are encouraging the use of CHP, in order to reduce the demand or overcome a bottleneck in the distribution network. New Jersey is offering incentives for installation of CHP in targeted areas. Transmission grid operators are also establishing programs to reward energy users who shed utility load by using on-site generators. However, the difficulty in determining and complying with the utility requirements can be an arduous task. A national standard for the interconnection requirements would

PHOTO 6. 360 kW cogen installation using six Capstone microturbine units in Woodland Hills, CA. Hot water byproduct loop connects to absorption chillers for air conditioning purposes. (Courtesy of Capstone Turbine Corp.)

be a help to the process, both in ensuring a safe installation and reducing the cost of design.

There are two main types of utility tariffs that can affect the economic analysis of a cogeneration system. These are back-up tariffs, consisting of supplemental and standby charges, and competitive transition charges, where the distribution services recoup their losses for someone leaving the system. It is important that these charges be identified for each particular installation and included in the analysis (California Energy Commission 2004).

Economics of Cogeneration Systems. The following example is based on a feasibility study for a multifamily housing complex in Syracuse, NY. The facility has an estimated average of electrical and DHW load of 7,000 kWh and 23,250 gallons per day, respectively. The goal of the cogen system is to produce as much electricity as possible while not exceeding demand for DHW. Any electricity not supplied by the system will be purchased from the grid, and the existing boiler that previously delivered all DHW requirements will make up any shortfall in DHW output. For cost purposes, a value of $ 0.105/kWh is used for electricity, and $7.11 per million BTU is used for natural gas. Note that the value used for the price of electricity is lower than that used elsewhere in this paper, because the large-scale residential customer is expected to receive a better retail price for electricity than a household customer.

The cost breakdown for the project is shown in Table 3. In this case, microturbine technology is used as the electrical generation system. Two 60 kW turbines are selected so that, running 18 hours per day (except for midnight–6 A.M. when DHW demand is expected to be low), the waste heat from the turbines can generate 20,805 gallons per day, or 89% of the total demand. Based on the DHW output and the heat input required to generate this amount, the electrical output is 2,160 kWh per day. In a region with a cold winter climate such as that of Syracuse, it would be possible to use the waste heat for space heating as well as DHW, allowing the turbines to run continuously and improving their utilization and total annual output.

Each turbine costs $85,000 including all materials and labor, for a total cost of $170,000. In addition, the project anticipates a substantial additional cost for maintenance of $15,768 per year, on the basis of a maintenance contract calculated at $0.02 per kWh produced. This calculation is conservative, in the sense that the existing gas-fired boiler would be used less in the new system and therefore should incur less maintenance cost, but these potential savings are not included. Electrical costs have been reduced by nearly $83,000 thanks to on-site generation of electricity, while gas costs have only increased by $28,000, so that the net savings from the project are about $39,000 per year. On the basis of these cost figures, the savings pay for the investment in the cogen system in a little over 4 years.

TABLE 3. Summary of cost and savings for example cogen project.

Number of turbines:	2
Total cost (mtls + labor)	$170,000
Daily electricity out, kwh	2,160
Daily dhw out, gallons	20,800
Reduction in elec cost per year	$82,782
Increase in gas cost per year	$27,620
Additional maintenance cost per year	$15,768
Net savings per year	$39,394
Payback period, years	4.3

Practical Considerations

- The majority of cogen units produce 480V power as their electric output, so if that is not the electrical service voltage at the site, a transformer will need to be added, at additional cost and loss of efficiency.
- The output of the cogen units varies with the outside air temperature, or the air entering the unit. Significantly more power is produced at lower temperatures, e.g. one unit produces 70 kW at 59°F (the usual rating temperature) and 92 kW at 0°F.
- Some outdoor units have a lower limit of temperature that they are able to operate on, so this should be taken into account for your area.
- The microturbine type requires a very high gas pressure into the unit, upwards to 100 PSIG; this is accomplished either with a separate gas compressor, or one contained within the unit. If it is the former, additional space must be made available for that piece of equipment. Likewise, some

models have the recuperator (the unit that recovers the heat from the exhaust stream) contained within the unit and some do not.

ON-SITE VERSUS OFF-SITE CLEAN ENERGY OPTIONS: A DISCUSSION OF THE PROS AND CONS

So far in this article we have considered a number of both on-site and off-site energy options for generating clean power. Not all options are available in both on-site and off-site versions. For example, in the US, solar is currently only available in the form of on-site PV systems (and also solar thermal water heating), since there are only a limited number of large-scale, remote solar power stations whose power is not generally on the open market as "green electricity."

The Case for Off-site Energy

If cost-effectiveness is the main concern and the buyer wants to get as many kWh of clean energy per dollar spent as possible, then off-site producers will have an advantage in many situations, because they are able to choose the site with the best possible resource. True, electricity from these sources must be marked up to reflect the cost of transmission over the grid; however, superior output at the source often overcomes this cost handicap. Let us return to the small-scale wind turbine in Example 1 above. What if the building owner opts for wind-generated energy from the grid? The turbines used to generate this electricity have many economic advantages. First, when wind power developers "prospect" for a location for a group of wind turbines (called a "wind farm" or "wind park"), they are free to choose the best possible locations, which typically are on top of windy hilltops, far from built-up areas (assuming permits are granted). For example, the Fenner wind farm on a ridge near Syracuse, NY, has average windspeeds of 17 MPH at 150 feet above the ground. Using the Rayleigh function approximation above, it can be shown that this increase of just 4.2 MPH over the small turbine in the example increases the amount of energy available in the wind per square foot of swept area by almost 2-1/2 times.

Large-scale wind turbines have other advantages as well. Because of their large size, it is more cost-effective to build them higher off the ground, where the winds are stronger—in many locations, raising a turbine from 65 feet to 150 feet off the ground can increase available power by 50–75%. There are also economies of scale in building larger turbines, so that they cost less per unit of rated capacity. Whereas the small turbine cost on the order of $3,000–4,000 per kW of capacity, not including installation cost, a large turbine in the 1-to-2 MW range may cost on the order of $1,000 per kW.

All of these advantages translate into a competitive cost per kWh for off-site wind energy. In desirable locations, large-scale turbines can generate electricity for as little as 3–4 cents per kWh. Even taking into account the cost of transmitting the electricity over the grid of perhaps 5–6 cents/kWh, and marketing and other costs, this source is very competitive with the 13 cents/kWh used in the examples.

The Case for On-site Energy Saving Options

Earlier, we made a distinction between a system that used fossil fuels more efficiently (Example 3), versus a system that replaces fossil fuels with renewable sources (Examples 1 and 2). In comparing the simple payback period for the three systems, the cogen system took only 4.3 years, versus between 8 and 22 years for the various renewable energy systems, depending on the scenario (See Table 4). This comparison is representative of how, in many situations, it is more cost-effective to invest in using fossil fuels more efficiently than in renewable energy. Renewable energy systems have no ongoing fuel costs but have high capital costs. They also have relatively low capacity factors—25% for the turbine or 10% for the PV system in the examples above—compared to devices such as the cogenerating microturbine, which in many applications may have a capacity factor of 60–90%. The combination of relatively low capital cost and high capacity factors give efficiency investments an advantage.

TABLE 4. Comparison of payback periods for on-site clean energy options.

Option	Payback [years]
Cogen system (example 3)	4.3
Wind turbine with rebates (example 1)	8 to 11
Solar PV system with rebates (example 2)	14 to 22
Wind turbine without rebates (example 1)	16 to 22

The Case for On-site Renewable Energy Options

Although they may be more expensive than investing in efficiency or buying clean power from the grid, on-site renewable energy has its own advantages. Here are four:

1. Potential for greater reliability: if a renewable energy system is built as an off-the-grid operation with battery banks and backup generator, it is no longer affected by grid blackouts. Also, a grid-tied system can be installed in such a way that if grid power is lost, the system can switch into a stand-alone mode and continue operating, given additional investment in batteries and controls. In certain applications, for example businesses where loss of merchandise or sales opportunities may be critical, not being vulnerable to extended blackouts has real economic value. Note that these benefits apply to the on-site cogen system as well.
2. High visibility: having a wind turbine or PV array on site makes an obvious statement about the building owner's commitment to renewable energy, and visitors to such a site may respond positively. This perspective gets into the area of human perception where trained "technologists" may be quite uncomfortable. Nevertheless, having a renewable energy system on site may actually bring in shoppers, clients, or future residents who otherwise would not have made the trip, and these visitors can help the bottom line. Given our current understanding of consumer preferences, it is probably also true that the dollar value of this contribution can only be estimated crudely, if at all.
3. Improved morale: the U.S. Green Building Council has identified improved morale and productivity as one potential benefit of working in a green building (USGBC 2003). In a business, government, or school setting, seeing renewable energy at work every day in one's building and knowing of its existence may make an employee or other occupant more enthusiastic about his or her workspace. As with point #2, this advantage gets into a subjective area that is not well researched or understood, and that may seem like shaky territory to some. However, USGBC has suggested that "proving the business case for the human and social benefits of green building . . . could prove to be vastly more rewarding in the long run" than the direct economic effects of saving energy and other resources.
4. The right combination of cost and environmental benefit: when choosing a clean energy option, a building owner may look at the available options and choose to invest in an on-site renewable system, even though it may cost more than other options. In this case, the builder may be asking a different question from the one we posed at the beginning. Instead of asking, "How can I achieve the goals of clean energy?", he may be asking, "Is the proposed on-site energy system within the range of what I can afford, in order to make the contribution to the environment that I envision?" The preceding points 1–3 may contribute to the choice of on-site renewable energy. The most important reason, though, may be the ability to make a more personal, local contribution to a sustainable energy future. Having ownership of the system, as opposed to buying energy from a system that someone else owns, may be its own advantage in this case.

PARTING THOUGHTS ON ENERGY COSTS AND FUTURE DIRECTIONS

In closing, let us return to the discussion of the relative costs of fossil versus renewable energy, and how they might change over time. Earlier we looked at reasons why fossil energy costs might go up or down. For renewable energy costs, the likely direction is down, since the industry has every incentive to lower the capital cost of its product so that it is more competitive with other alternatives in the open market. There is probably less room to improve in the fossil market, since many improvements have already been made. Furthermore, relative to the uncertainty surrounding fossil energy costs, a renewable energy system, once installed, has more predictable costs since the output is usually known from year to year, within a 10–20% margin of error. One caveat here: global climate change, one of the very reasons for using renewable energy, may also contribute to long-term changes in weather patterns that will alter the output from renewable energy systems in some locations! At present, however, there is every indication that this risk is not as great as the risk involved in fluctuating fossil energy costs—witness the wild fluctuations recently in the cost of a therm of gas or barrel of oil.

A second point is that, for simplicity, in this article we assumed a constant value of electricity, in constant dollars, over time for the purposes of calculating annual savings of energy costs and payback periods. Over project lifetimes of 20 years or more, such as the PV array example, there is a very real chance that the relative cost of electricity will in fact change, and that this change will alter the economics of the investment. Given the twin factors of scarcity of oil and gas, and the need to make new investments to protect the environment from the effects of greenhouse gases, we might speculate that fossil energy costs will go up and not down, helping renewable energy.

Lastly, we might ask how these trends might affect the renewable energy market as a whole. There appear to be two segments within this market. The first segment is the group committed to clean energy in any case, and for the foreseeable future it will sustain the market for both on- and off-site renewable energy at a certain level. These customers typically are well-educated, concerned about the environment, and have the resources to act on these convictions by paying extra for clean energy. The second segment is the customer group that is interested in clean energy, but whose ability to invest in it will depend on its cost relative to the cost of conventional energy. This segment is potentially much larger than the first, so whether we have 5% or 25% of our energy from renewable energy sources 10 or 20 years from now will largely depend on how technology, resource, and environmental factors play out.

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