

A Conspectus on US Energy

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An athlete sitting on a bicycle seat can produce about 100 watts of useful power on a long-term basis. After 10 hours, the athlete produces 1,000 watt-hours, or one kilowatt-hour (kWh). While some people balk at the notion of having to pay (say) 8.5 cents rather than their present 8 cents for that kilowatt-hour, what would they have to pay the athlete for ten hours of hard labor? And what would it cost for that kWh if we had to do nothing more than feed the athlete?

All in all, the US (of 310 million people) uses about 100 exajoules (EJ, equal to 10^{18} joules) per year from all sources and for all uses. On a year-round average basis (3.16×10^7 s), then, we consume 10.2 kW per capita. Due to the recession this figure is down 7% from 1997 when we used 107 EJ, amounting to 10.9 kW per capita. All in all, each of us has the energy equivalent of over 100 slaves working for us night and day.

Coal, oil, natural gas, uranium, firewood, hydro, wind, and solar all provide energy that is far cheaper than human—or indeed, animal—labor. It is no wonder that energy drives everything we do.

Information Source

The best source for US energy use is the Energy Information Administration (EIA) of the Department of Energy (DOE), especially the *Annual Energy Review (AER)*, a PDF file of 446 pages length [1]. It is a goldmine of energy information.

Unfortunately, the *AER* uses a mélange of units. Primary thermal energy is expressed in BTU, and electrical energy produced is in kWh. For example, the *AER* says that we used 38.89 quadrillion BTU (2009) to produce electricity. Another table says we generated 3,953 billion kWh of electricity. Translating to joules, we find that 41.03 EJ of heat produced 14.23 EJ of electrical energy, implying an overall efficiency of 34.7%.

We also find that hydropower consumed 2.682 quadrillion BTU and produced 272.1 billion kWh. But hydropower stations do not use heat as the energy source! Translating again to joules, we find 2.83 EJ of “heat input” to produce 0.98 EJ of electrical energy, implying an efficiency of 34.6%. The actual efficiency of hydropower stations is in excess of 90%, so where did that BTU figure come from? The EIA simply invents an as-if number to represent how much thermal energy would have to be used to produce the 272.1 billion kWh if heat engines instead of hydropower stations were used.

A table in the Appendix of *AER 2009* has “Heat Rates for Electricity,” which values are *reciprocal* efficiencies expressed in BTU/kWh. For example the 2009 value for fossil-fueled plants gives 9,854 BTU as being required to produce 1 kWh. Given that 1 BTU = 1,055 J, this says that 10.4 MJ of heat was required to produce 3.6 MJ of electricity; the efficiency is 34.6%.

Historical Perspective

In the early days of the nation, firewood provided the majority of the energy consumed. Of course, there was some water power, and there were draft animals. Undoubtedly, there was some coal usage here and there, but the country had an abundance of

trees—too many, in fact, because the forests took up land the settlers wanted for farming. There are records of firewood consumption dating back to the days of Benjamin Franklin, as well as records of coal consumption while the industrial age progressed. Figure 1 shows the historical energy usage since 1635.

Annual US Energy Consumption 1635-2007

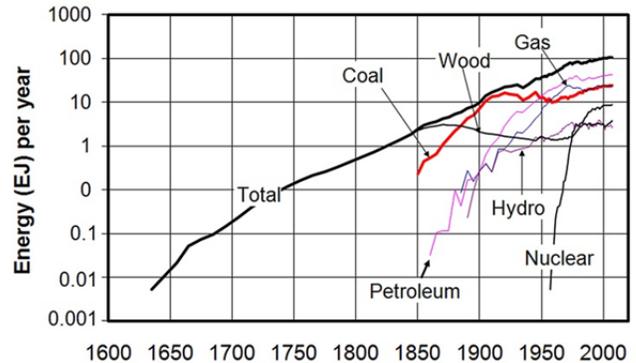


Figure 1: US energy consumption 1635-2007 from various sources, and the total. Notice the logarithmic scale. We use about 200,000 times as much energy as did the country shortly after Pilgrims arrived at Plymouth Rock.

In Figure 1, we see that the nation has increased its energy consumption by a factor of about 200,000 since 1635. But what about energy consumption *per capita*? We can construct a graph of historical per-capita energy consumption, as shown in Figure 2.

Per-Capita Energy Use Rate (Average kW [thermal] per person)

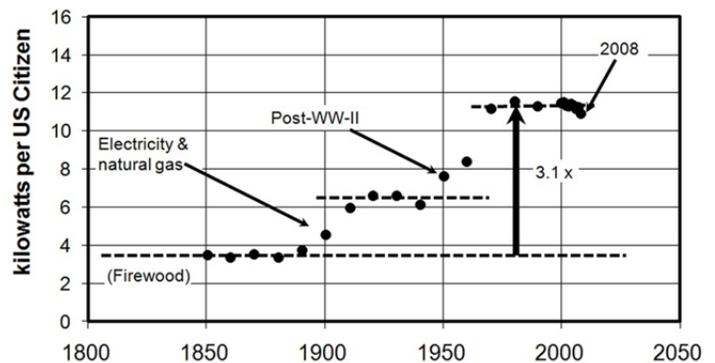


Figure 2: US per-capita energy consumption expressed in year-round average kilowatts per US citizen since 1850. On a per-capita basis, we use about 3.1 times as much energy as did our pre-Civil War forefathers.

By the middle of the 1800s, the railroad industry was thriving, and by 1900, the sources and uses of electricity began to expand, as did consumption of natural gas. Meanwhile, efficiency was increasing on all fronts. Woodstoves replaced fireplaces, whose *best* efficiency was around 9%. Houses were insulated better. Lighting from candles and other open fires had been well below 0.1% efficient. The first steam engines were about 0.05%

efficient, and now combined-cycle power plants have recorded efficiencies as high as 60%, an improvement by a factor of 1,200. Accordingly, our per-capita consumption of energy has increased by a factor of only 3.1. As University of Colorado Professor Al Bartlett has kindly reminded me, the energy consumed in the US is not necessarily the same as the energy consumed in *behalf* of the US. Much of our manufacturing is done overseas. (As well, much of our manufacturing within the US is of products that are exported.) Still, most people you'll ask will suppose that we use tens to hundreds of times as much energy per capita as our forebears.

As an example of increasing efficiency, see Figure 3, which shows that the overall efficiency of the US electrical system from fuel to end use has increased from 21% in 1950 to 33% in 2009. Since most of our electricity is produced by heat engines (steam engines and gas turbines, primarily), the large inefficiency stems from the demands of the second law of thermodynamics. Only about 7% of the electrical energy is lost in transmission and distribution.

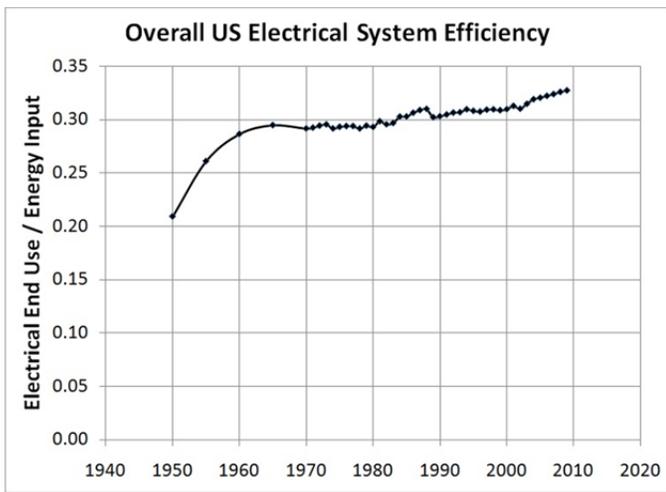


Figure 3: Overall electrical system efficiency since 1950.

Two aspects of energy are subject to the most rapid change. The overall quantity of energy grows with population, which has approximately doubled since 1950s. The other rapidly changing number is the increasing role of electricity. Figure 4 shows that the fraction of our primary energy used for production of electricity has grown from 14% in 1950 to 41% at the present. Television was not terribly common in 1950, and all telephones were connected by wires. "Radio" meant a handful of AM stations. Most people had never heard the term *computer*, and the computers that existed were few and far between.

Another factor in the growth of demand for electricity is air-conditioning. In the 1950s, movie theaters were often air-conditioned to lure customers during hot summers. Homes were rarely air-conditioned.

Our cellphones, iPods, Kindles, Nooks, and the like require very little power to run *themselves*; however, the communication system that makes them work requires a tremendous amount of power. There are hundreds of "data centers," non-descript buildings here and there that handle all of the messages that are sent over wires and fiber-optical cables [removed comma] and by wireless communication. Typically, these centers are designed to consume over a kilowatt per square meter of floor space for running the electronics, plus air-conditioning systems to keep the

electronics from overheating. Data centers that consume many tens of megawatts are common.

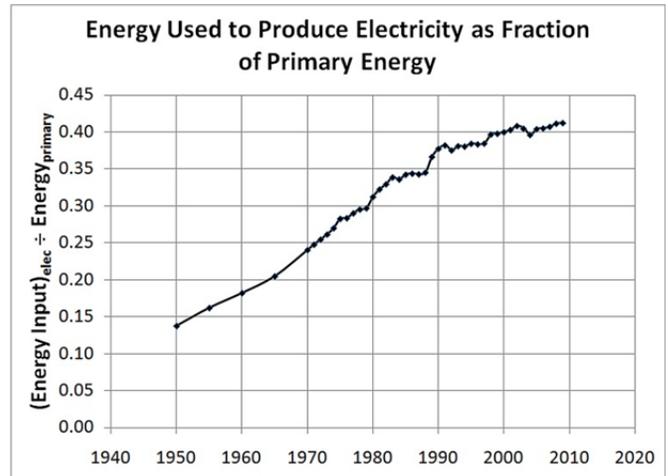


Figure 4: In 1950, about 14% of our primary energy went into production of electricity. This figure has grown to 41%.

The Present

Eighty-five percent of our energy comes from coal, oil, and natural gas (See Figure 5). Petroleum (40%) is used almost exclusively for transportation, and nuclear energy (8%) is used exclusively for producing electricity, as is the majority of coal.

US Energy Sources 2007

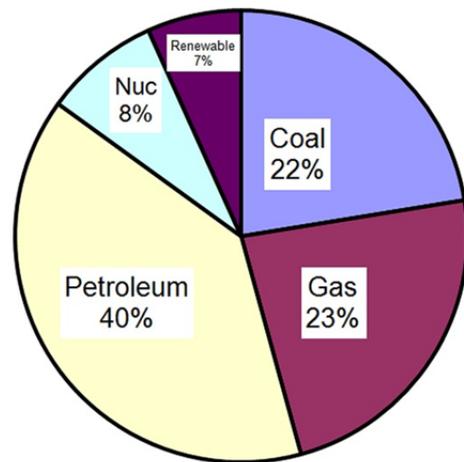


Figure 5: US Energy Sources, 2007. Notice that 85% of our energy comes from coal, oil, and natural gas.

The designation *Renewable* in Figure 5 refers to hydroelectric power (35% of the renewable fraction), firewood (24%), other biofuels (20%), wind (9%), waste (6%), geothermal (5%) and solar (1%). Of the solar contribution, the solar/thermal/electric is about four times as large as the solar/photovoltaic contribution.

Figure 6 shows that the largest source of electrical energy is coal (50%) followed by nuclear fission (20%) and gas (19%). Of the renewables, the conventional sources (hydro, wood, waste, and geothermal) are responsible for 90%; wind and solar account for 10% of the renewable electricity, or 1% of all electricity. Note that if some magic source produced 100% of our electricity tomorrow, it would have only a minuscule effect on our

consumption of petroleum, because oil is primarily used for transportation, not for producing electricity.

US Sources of Electricity

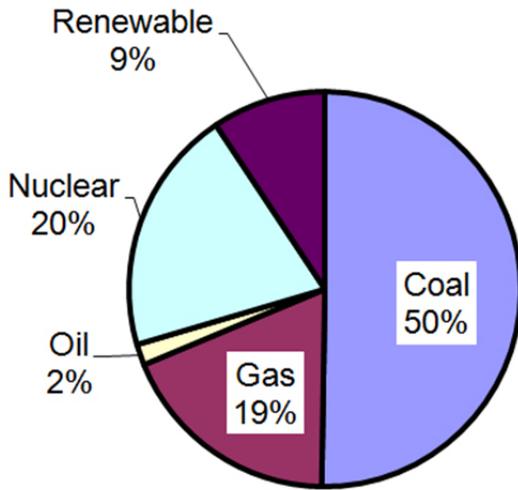


Figure 6: The sources of electrical energy, 2007. Hydropower is responsible for 66% of the renewable electricity, and 7% of all electricity.

It is useful to know that when the total electrical consumption is averaged over all citizens, the per-capita consumption of electricity is about 1,300 watts. That is, a city of 700,000 uses 1,000 MW on the average to run its homes, factories, businesses, and everything else.

Who uses all of that energy? Figure 7 shows the eventual users of energy, whether by direct usage (such as natural gas burned in home furnaces) or by indirect usage, *viz.*, from electricity whose sources have been properly allocated to the end user. Roughly speaking, transportation and industry each consume almost one-third of the energy, while residences and commercial establishments each use one-fifth.

Energy Usage, US 2007

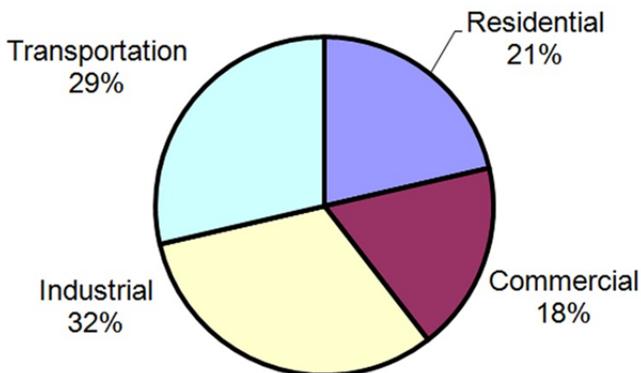


Figure 7: Consumption of US energy by sector.

Physics

All of the information except for population data above has come from *The Annual Energy Review*, and all of it is about how society obtains and uses energy. It is now time to do—and to suggest—some calculations.

Fuels

Let us begin with the human. Each of us has a daily intake of something like 2,000 food calories. Each calorie is 4186.8 joules, and a day is 84,600 seconds. The fuel-input rate is therefore 96.9 watts, which can be rounded to 100 watts.

A car travels at 60 miles per hour, and gets 30 miles per gallon. We can calculate the fuel-input power from the consequent 2 gallons per hour, and obtain 77.8 kW (the equivalent of about 16 electric oven with every burner fully on.

Batteries are not fuels, but they do store energy. A new 12.6-volt automobile battery stores about 60 ampere-hours of charge, hence the stored energy is about $\frac{3}{4}$ of one kWh. In other words, the battery stores roughly a dime's worth of electrical energy at utility prices. (How many coulombs? How many joules?)

Wind Turbines

A horizontal column of air of cross-sectional area A and length L , traveling at speed v has kinetic energy

$$KE = (1/2)mv^2 = (1/2)\rho Vv^2 = (1/2)\rho ALv^2 \quad (1)$$

where ρ is the density and V is the volume of the column, given by AL . Of course, we take A to be the cross-sectional area πR^2 swept out by the spinning blades of the wind turbine. During some time interval $t = L/v$, all of that energy sweeps past a chosen point, so the rate of energy arrival is

$$\frac{KE}{t} = \frac{(1/2)\rho\pi R^2 Lv^2}{L/v} = (1/2)\rho\pi R^2 v^3 \quad (2)$$

Equation (2) represents energy per unit time, but not power, because power refers to energy converted from one form to another. The wind turbine converts some fraction called the *power coefficient* k to useful energy. If the wind turbine converted *all* of the arriving energy, the air would stop, thereby blocking further air from reaching the turbine.

The density of air is about 1.3 kg/m^3 . Still, Equation 2 needs information about the behavior of real wind turbines. Websites www.gewind.com and www.vestas.com provide actual performance curves representing power output versus wind speed. Using the diameters given for the various products and a convenient wind speed (10 m/s), one can calculate that the power output is given closely in SI units by

$$P = (2/3)R^2 v^3 \quad (3)$$

That is, power in watts is $2/3$ of the product of the square of the radius in meters and the cube of the wind speed in meters per second. (How much power for a 100-m diameter turbine in 10m/s wind? ...in a 5 m/s wind?)

The performance curves, however, are more complicated. Below about 4 meters per second, the speed is too low to generate any power at all. Above about 12-13 m/s (rather uncommonly high speeds), the power is constant (at the maximum power rating), a feat achieved by "trimming" the blades to decrease the efficiency. Above 25 m/s the wind turbine is shut down entirely to keep it from self-destruction.

There is an illusion that the blades of industrial-scale wind turbines turn slowly. Indeed, their rate of rotation is low (typically about 15 revolutions per minute), but the speed of the tips of the blades is 6 or 7 times the wind speed, reaching

NASCAR speeds. (Tip speed for Vestas 1.8-MW, 90-m diameter turbine at 14.5 RPM?)

The low rotation rate is generally incompatible with those of generators, so most wind turbines have gearboxes that increase the rotation rate by factors of 30 to 120 (depending upon the number of poles in the generator). The gearboxes have shown themselves to be the weakest link in the machines.

The most vexing problem with wind turbines is the extreme variability with wind speed as shown in Equation 3. If the wind speed suddenly drops to half-value (say, from 10 m/s to 5 m/s), the power drops by 87.5%. When the wind fraction of the power on the line is low, the utility merely treats the variations as the negative of the variations in load that they normally handle anyway. Compensation is handled by “spinning reserve,” conventional power plants that are run at about half-power to compensate both decreases and increases in demand. The more wind power there is on the line, the more spinning reserve is required, and that power is always more expensive than power from baseload units that produce full power 100% of the time.

Spacing

Because wind turbines extract kinetic energy from the moving air, turbines should not be placed closely behind one another. Moreover, turbulence from one turbine can be damaging to another. Typically, turbines are placed about 7-10 diameters apart, but a new paper [2] says that 15 diameters is better. But whatever the spacing, a simple rule emerges. Since the power output is proportional to R^2 , doubling the diameter quadruples the power. But doubling the diameter also requires that the turbines be placed twice as far apart—in each direction—thereby requiring four times the land area. The power per unit land area is therefore independent of turbine radius. Most very good wind farms produce about 12.5 kW/ha¹ on a year-round average basis. (How many hectares to produce as much energy in a year as a large conventional 1,000-MW power plant produces? How many square miles?)

When winds are predominately from a certain direction, the turbines can be placed closer to one another, typically 3-5 diameters apart on a side-to-side basis. Wind “farms” thus designed can exceed the 12.5 kW/ha figure.

Capacity Factor

A 1-MW generator driven by a child’s pinwheel would produce no power at all, because the little toy couldn’t even turn the massive generator. A 1-watt generator driven by a 100-meter diameter wind turbine could probably be arranged to produce 1 watt all the time. The *capacity factor*—defined as year-round average power divided by nameplate power—for these extreme cases would be 0% and 100%. Obviously, the capacity factor is determined by the relative size of the generator compared to the size of the turbine.

Wind systems these days are designed to have a capacity factor of about 35%; that is, a 2.0-MW unit is expected to produce 700 kW on a year-round basis.

Hydropower

While wind turbines extract kinetic energy from air, hydropower uses gravitational potential energy. A mass M of water descends a height h , and converts potential energy Mgh in time t to work,

turning a water turbine that turns a generator. The overall efficiency η is about 95% in large hydropower stations. Usually, one measures volume of water instead of its mass, so the power, namely work W per unit time, is

$$P = \eta \frac{W}{t} = \eta \frac{Mgh}{t} = \eta \rho gh \frac{V}{t} \quad (4)$$

With the density of water being 1,000 kg/m³, and the efficiency taken at 90%, we obtain the equation in SI units

$$P = 8800h \frac{V}{t} \quad (5)$$

Illustrative problem: Suppose a mass M were to descend from the altitude of a jet plane (say, 10,000 m), how large would M have to be (assuming 100% conversion efficiency) in order to evaporate one kilogram of water already at the boiling point? (Heat of vaporization = 540 kcal/kg = 2.26×10^6 J/kg.) We’ll leave the exact arithmetic to the student; suffice it to say that M is approximately the mass of an 8-year old.

Another one. The state of Connecticut (land area = 12,549 square kilometers) annually gets one meter of precipitation. If a dam of 100 meters height were to be kept full, letting Connecticut’s precipitation go through the associated hydropower turbine at a sustainable rate, how much power would be produced? Again, we’ll let the student do the exact arithmetic; the answer is roughly a third of the output of a single large conventional power plant.

We can now see why hydropower generates only 7% of our electricity. It takes massive flow of water descending from great height, and the number of such sites is limited.

Solar/Thermal/Electric units

Figure 8 is a photograph of part of a massive solar energy project in the Mojave Desert. The parabolic reflectors concentrate sunlight onto a pipe through which an oil called *Therminol* flows. The heated Therminol is pumped through a heat exchanger to boil water to run a steam turbine, thence to generate electricity. The nine fields at Daggett, Kramer Junction and Harper Lake together generate 6.5×10^{11} watt-hours a year on a long-term average. (What is the average power in watts?)



Figure 8: Solar/thermal unit (“Solar Energy Generating System,” SEGS) in Daggett, California.

¹ A hectare is 100 ares (100 m²), so 1 ha = 10⁴ m².

The *Annual Energy Review* lists solar/thermal/electric sources together with solar/photovoltaic, as *Solar/PV*. In 2009, the total generation was given (to one significant figure) as 0.8 billion kWh, or 8×10^{11} Wh. Therefore the Solar Energy Generating System (SEGS) units in the Mojave Desert are responsible for $6.5/8 = 81\%$ of the Solar/PV contribution.

Biomass

Drymatter (dry wood, grass, leaves, corn...) has a heat content of about 15 MJ/kg. How much drymatter comes from how much land area? It depends on many things, of course.

Let us look at corn ethanol (alcohol made from corn). *AER 2009* tells us that a bushel of corn yields about 2.75 gallons of ethanol. Each gallon yields 28 MJ. The gross heat of corn is said to be 0.392 million BTU per bushel. Therefore 77 MJ in the ethanol comes from 414 MJ in the corn, an efficiency of 19%.

In prime corn country, Iowa produces about 160 bushels of corn per acre. In terms of energy, the gross heat content is 16.4 MJ/m² per year, or 0.52 watts (averaged around the year) per square meter of land. That's 0.1 watts of ethanol energy per square meter, with no heed paid to the energy required to do the farming and conversion to ethanol.

Appendix

The topics discussed in this paper are simple, but made complicated by the use of non-SI units. Fortunately, the energy values found in *AER 2009* are limited to the BTU and the watt-hour, both with various prefixes. The time unit is almost always either the second or the year. *AER 2009* does have some useful appendices about such matters as the heat content of some fuels.

We presume that readers of *The Physics Teacher* know the *Système International* prefixes. Following are some calculable numbers that it is well to memorize:

$$\begin{aligned} 1 \text{ day} &= 86,400 \text{ seconds} \\ 1 \text{ year} &= 3.16 \times 10^7 \text{ s} \cong 10\pi \text{ Ms} \\ 1 \text{ year} &= 8,760 \text{ hours} \end{aligned}$$

Units for energy are actually defined in terms of the joule.

Examples are:

$$\begin{aligned} 1 \text{ BTU} &= 1,055.055853 \text{ J} \\ 1 \text{ kWh} &= 3.6 \times 10^6 \text{ J} \\ 1 \text{ kcal} &= 4,168.8 \text{ J} \end{aligned}$$

Next we list some "heat values" of fuels, namely the energy released when the fuels are burned in bomb calorimeters that retain all combustion products (thereby retrieving the latent heat of water released).

$$\begin{aligned} 1 \text{ gallon of gasoline} &= 132 \text{ MJ} \\ 1 \text{ kg hydrogen} &= 120 \text{ MJ} \\ 1 \text{ kg methane (CH}_4\text{)} &= 50 \text{ MJ} \\ 1 \text{ kg petroleum (any)} &\cong 43 \text{ MJ} \\ 1 \text{ kg ethanol} &= 26.8 \text{ MJ} \\ 1 \text{ kg coal} &= 24 \text{ MJ (US util. average)} \\ 1 \text{ kg drymatter} &= 15 \text{ MJ} \\ 1 \text{ cubic foot natural gas} &= 1.09 \text{ MJ} \end{aligned}$$

Solar sources can always be expressed in units of power per unit of land area. These land areas are in common use.

$$\begin{aligned} 1 \text{ acre} &= 4047 \text{ m}^2 \\ 1 \text{ hectare (ha)} &= 10^4 \text{ m}^2 \\ 1 \text{ mi}^2 &= 2.59 \times 10^6 \text{ m}^2 \end{aligned}$$

References

- [1] *Annual Energy Review 2009* is available at <http://eia.doe.gov>. Search for AER. There will be a link to *Annual Energy Review*. On that page there are many tables, but importantly there is a little box referring to "Previous Editions of AER." That page has a button to download the book as a single PDF file.
- [2] Johan Meyers and Charles Meneveau, "Optimal turbine spacing in fully developed wind-farm boundary layers," *Wind Energy* (2011, accepted for publication) says, "For realistic cost ratios, we find that the optimal average turbine spacing may be considerably higher (~15D) than [sic] conventionally used in current wind-farm implementations (~7D)."

Howard Hayden received his B.S., M.S., and Ph.D. in physics at the University of Denver. He retired as Professor Emeritus from the University of Connecticut, where most of his research involved accelerator-based atomic physics. He has been interested in societal energy since his undergraduate days, and published his first paper in the subject in 1981. In 1999, he moved to his home state of Colorado. Email: corkhayden@comcast.net.