ECONOMICS OF WIND SYSTEMS

If one of you is planning to build a tower, he sits down first and figures out what it will cost, to see if he has enough money to finish the job. Luke 14:28.

In earlier chapters we have determined the power and energy production from various types of wind turbines in various wind regimes. The economic goal of maximizing the energy output per dollar of investment has been mentioned several times. We now turn to the matter of determining the total capital investment and operating cost for wind electric generators, so that we can determine the unit cost of electricity. The fuel (wind) may be free, but the equipment necessary to use the fuel tends to be expensive, so economic studies are quite important.

The unit cost of electricity can be determined in a straightforward manner from a knowledge of capital investment and operating costs. The value of the electricity is somewhat more difficult to determine, but must be calculated before intelligent investment decisions can be made. The value must exceed the cost before the purchase of a wind machine can be justified. The ratio of value to cost must be as good as that for alternative sources of electricity before wind can be justified over these alternatives.

The value of wind generated electricity to an electric utility is determined by its fuel savings and by its capacity credit. When the wind is blowing, less oil and coal need to be burned, which represents a savings to the utility. Also, if the utility is able to delete or defer some new conventional generation as a result of adding wind machines, then this represents additional savings to the utility. The effective capacity of wind generators and the associated capacity credit was treated in some detail in Chapter 5.

The cost and value of wind generated electricity will be determined from standard economic models, assuming "business as usual." This means that we assume ample supplies of natural gas, oil, coal, and nuclear fuel, ready credit to build new generating plants, and no significant political changes. Hidden costs such as air pollution and nuclear waste disposal are ignored, at least until the last part of the chapter. We then observe that many of the plausible changes in "business as usual" operation tend to favor wind generators over conventional generation. Some of these changes will be discussed, but historical methods of evaluating alternative energy sources in general, and wind generators in particular, will be presented first.

1 CAPITAL COSTS

A wind turbine used for electric production contains many components. At the top of the tower of a horizontal axis turbine are the rotor, gearbox, generator, bedplate, enclosure, and various sensors, controls, couplings, a brake, and lightning protection. At the foot of the tower are the transformers, switchgear, protective relays, necessary instrumentation, and controls. A distribution line connects the wind turbine to the utility grid. Land, an access road, and construction are also required to have a working system. The *capital costs* of all these items must be carefully examined in any engineering study.

Some capital costs, such as distribution lines, land, and access road, can vary widely with the site. These costs would be minimized by placing the wind turbines along an existing road. This would be the normal practice in the Great Plains where there are no major variations in topography. In other parts of the United States and the world, wind turbines will be placed at the best wind site, which may be on top of a mountain several kilometers from roads and power lines. In such cases, these costs may be a substantial part of the total.

The cost per kW of maximum power output varies with the size of wind turbine. Costs of components per unit of size tends to decrease as size increases. For example, Fig. 1 shows the variation of cost of electrical generators with size. Similar curves will be valid for the transformers, distribution line, and other electrical equipment. In this figure, *dc* and *ac* refer to conventional dc and ac machines, both of which require a field current supplied from another source for operation. This increases the cost above that of the machine itself, and also contributes to the losses. The curve marked *PM ac* refers to an ac generator with its field supplied by permanent magnets. This is a simpler machine and potentially more efficient, which makes it desirable for smaller wind turbines. The dc machines cost about twice as much as the ac machines of equal rating, because of greater physical size and complexity. The dc machines tend to be less reliable because of the commutator, and the combination of poorer reliability and greater cost will probably restrict their use on wind turbines.

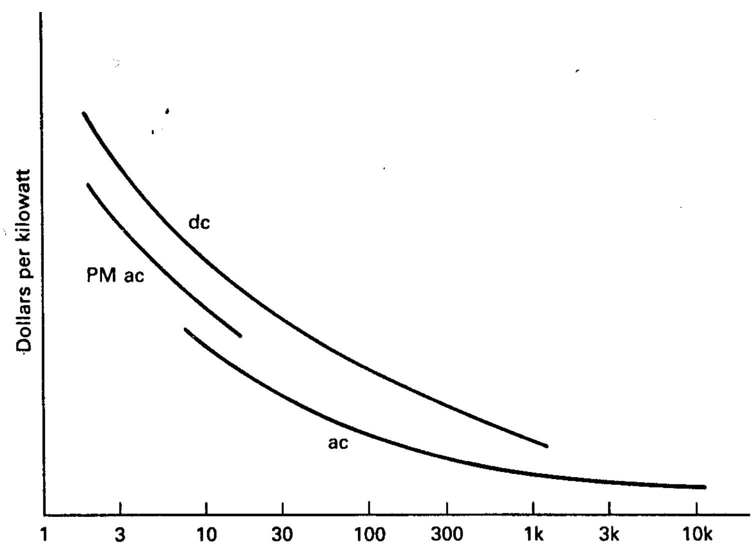

Figure 1: Relative costs of electrical machines.

Construction costs per unit of capacity also tend to go down as the capacity increases.

That is, a tower of double the rating does not usually require double the work to install, at least up to some critical size where locally available equipment and personnel are no longer adequate. On the other hand, the mass of material used increases as the cube of the rotor diameter while the rating only increases with the square of the diameter. Mass is proportional to volume while rating is only proportional to area. Since cost is related to mass, there will be a point where economics of scale are overcome by this basic law, and a turbine larger than some critical size will cost more per kW of maximum power than a turbine nearer this critical size. The critical size will vary with the assumptions made about cost variations, but several detailed studies have indicated that 1500 to 2500 kW may be close to the critical size[11, 13, 8]. Of course, the MOD-5A and MOD-5B are rated at more than 6000 kW, indicating a rather broad range of possible critical sizes.

Once a size has been selected, even more detailed cost studies can be made. The results of independent studies can vary widely, so caution needs to be used[9]. Golding[7] reports the results of three studies performed shortly after World War II which are reproduced in the first three columns of Table 8.1. These studies were all for conventional horizontal axis propeller turbines and were made by people experienced in the construction and operation of large wind machines. The differences between studies are substantial, perhaps illustrating the difficulty of the process.

The fourth column in Table 8.1 is the result of a study on a conceptual 200-kW horizontal axis wind turbine, called the MOD-X in that study[4]. The study was made by the Lewis Research Center after their experiences with the MOD-0 and MOD-0A. The conceptual design for the MOD-X included two pitchable rotor blades mounted on the low speed shaft of a three stage, parallel shaft gearbox. They chose a synchronous generator rated at 200 kW and 1800 r/min. The tower was to be a cantilevered rotating cylinder mounted on a dirt filled factory precast concrete vault foundation. The turbine was to have a teetered hub and a passive yaw drive system. Rated wind speed was 9.4 m/s (21 mi/h) at the hub height of 30 m.

This design resulted in significant cost reductions for foundation, yaw control, and installation, which makes the blades, tower, and gearbox appear relatively expensive as compared with the earlier designs. The predicted cost for the 100th production unit was $153,360 in 1978 dollars not including administrative and engineering costs and overhead, and $202,810 including all costs. This resulted in a cost of electricity of 4.34 cents per kWh at a site with an average windspeed of 6.3 m/s at 10 m height for their assumed economic conditions. We shall see later in the chapter how one determines such a figure for cost per kWh.

Table 8.1 Analysis of Construction Costs for Large Wind Turbines

	British Design	Smith-Putnam	P.T. Thomas	MOD-X (200 kW)
Blades(%)	7.4	11.2	3.9	19.6
Hub, blade supports, blade shanks, bearings, main shaft, nacelle(%)	19.5	41.5	5.9	15.2
Tower(%)	8.1	7.7	11.2	20.6
Gearbox(%)	16.7	9.5	2.3	16.5
Electric generator and installation(%)	12.5	3.4	33.6	7.6
Control equipment for speed, yaw, and load(%)	4.4	6.5	8.3	4.4
Foundations and site work(%)	31.4	16.6	20.3	16.1
Engineering(%)	-	3.6	14.5	-
	100.0	100.0	100.0	100.0
Rotor diameter(m)	68.6	53.3	61.0	38.1
Rated power(kW)	3670	1500	7500	200
Rated wind speed(m/s)	15.6	13.4	15.2	9.4
Production quantity	40	20	10	100

Another difference between the three earlier studies and the 1979 study is the improved technology. There have been improvements in the technology of each of the turbine components since 1950, and breakthroughs in at least two areas. These areas are the microcomputer control and the large computer analysis of the turbines. The Smith-Putnam machine required an operator to be present 24 hours per day to check meters, take the machine off the utility grid when the wind speed got too low, and resynchronize the generator with the grid when the wind speed increased. All these functions are now handled automatically by microcomputers. This reduces the operating costs substantially, improves the machine's performance, and reduces the possibility of the machine being damaged by operator error.

Also, the design of the Smith-Putnam machine was accomplished by the use of slide rules and mathematical tables. The design went through about six iterations but really needed several more which could not be allowed because of time constraints. Towers and blades are now designed with large computers, which have the potential of designing adequate structures which are not excessively heavy or expensive. Cost is always related to the mass of materials used, so lighter designs will improve the economic feasibility of wind turbines. The Boeing MOD-2, for example, was designed with a soft tower, which has 27 percent less mass per kW of rating than the stiff MOD-1 tower. This helped the MOD-2 to be more economically competitive than the MOD-1.

The above results have all been for large wind turbines. It is interesting to compare these results with similar results for small machines, to see if there are any effects of size. Results of a study on small machines[6, 2] are given in Table 8.2. Column one gives the cost percentages for machines currently available in 1980 and column two gives the cost percentages predicted for second and third generation machines in 1990.

TABLE 8.2 Construction Costs for Small Wind Turbines(%)

	1980	1990
Rotor and hub	12.0	20.5
Controls	6.0	6.6
Transmission	11.0	14.5
Generator/power conversion	7.0	11.6
Frame	8.0	2.4
Tower	18.0	7.5
Installation	20.0	25.6
Distribution	16.0	9.5
Shipping	2.0	1.8
	100.0	100.0

We see in this table that the frame and tower are two components which have a good potential for cost reduction, from 26 percent to 10 percent of total cost. The cost of distribution (dealerships, service groups, etc.) would appear to have some potential for cost reduction. As the percentage of these cost components is reduced, then other components become relatively more expensive. We see installation increasing from 20 to 25 percent of the total cost, indicating a need for considerable innovation in this area.

There are no major differences between projected percentage costs for the large and small turbines. Major cost components are blades, transmission, tower, and installation for all turbines, indicating that these components need to be carefully studied for possible cost reductions.

One of the challenges of economic studies is to estimate the cost of the installed wind turbine when it is being produced in large quantities. The cost of the initial few machines is quite high because of many specially made parts and substantial amounts of hand labor while later machines are able to take advantage of higher volume production. A decrease in cost per unit of product with increase in volume has been found to occur in a wide variety of areas, including Model-T Fords, aircraft, steel production, petroleum refining, and electric power generation. The classic example in recent times has been the hand-held calculator, along with other integrated circuit components.

This decrease in cost has been formalized by *learning curves.* These are widely used in many different industries. They are developed from the following mathematical model. If y represents the cost of an object while x represents the cumulative volume, then the *normalized incremental cost* dy/y is assumed to be related to the *normalized incremental volume* dx/x

by the differential equation

$$\frac{dy}{y} = -m\frac{dx}{x} \tag{1}$$

The parameter m is a constant of proportionality and the sign is negative because the cost decreases while the volume increases. We integrate this equation from the cumulative volume x to the volume $x(2^n)$. The cost is decreasing from y_1 to y_2 while the cumulative volume is doubling n times. The result is

$$\ln\frac{y_2}{y_1} = -(mn)\ln 2 \tag{2}$$

Solving for y_2 yields

$$y_2 = y_1 e^{-(mn)\ln 2} \tag{3}$$

The slope s of the cost curve is defined as

$$s = e^{-m\ln 2} \tag{4}$$

The cost y_2 after n doublings of volume is then

$$y_2 = y_1 s^n \tag{5}$$

The plot of y_2 versus n is a straight line on log-log paper. Figure 2 shows plots of normalized y_2 (for $y_1 = 1$) for slopes of 0.95, 0.9, 0.85, and 0.8. Given the cost of the first unit and the slope of the learning curve, one can estimate the cost of the tenth or hundredth unit of production, as well as all intermediate values.

We normally think in terms of the cumulative production volume x rather than the number of volume doublings n, so we need a relationship between n and x. It can be shown that the value of n for an increase in volume from x_1 to x_2 is

$$n = \frac{\ln(x_2/x_1)}{\ln 2} \tag{6}$$

The choice of slope s is critical to economic studies. This requires information about other learning curves from the past as well as careful estimates about how manufacturing costs should go in the future. Historical research has shown[5] slopes of 0.86 for Model-T Fords, 0.8 for aircraft assembly, 0.95 for electric power generation, 0.79 for steel production, and 0.74 for hand-held calculators. Various parts of the wind turbine would be expected to show different learning curves. Components such as blades, hubs, and gearboxes that are essentially unique to wind turbines would have smaller values of s. Electrical generators, on the other

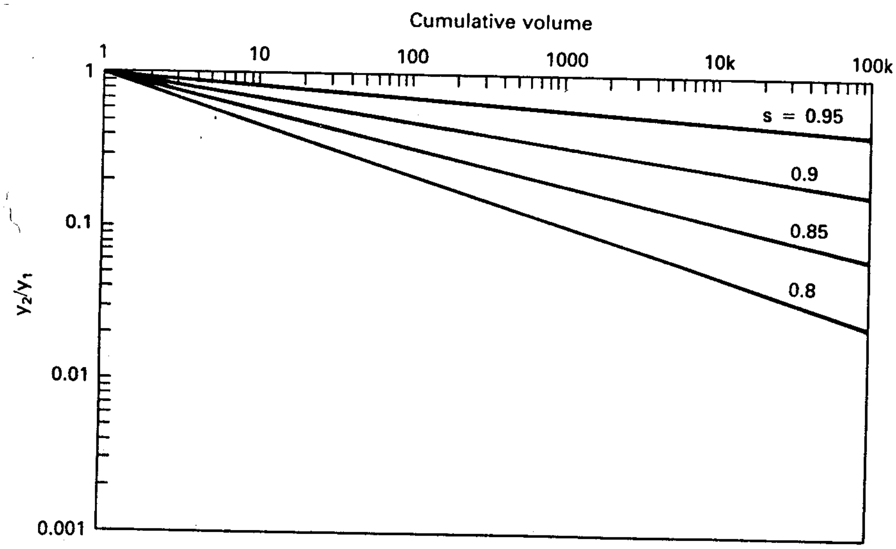

Figure 2: Normalized cost y_2/y_1 versus cumulative volume for several learning curves.

hand, represent a very mature technology with a large cumulative volume so very little cost reduction would be expected for this component. Other components would have intermediate values of s.

Example

The first unit of a new device costs \$1000.00. The device is estimated to follow a $s = 0.83$ learning curve. What is the cost of the hundredth unit?

The value of n would be

$$n = \frac{\ln(100/1)}{\ln 2} = 6.64$$

The cost y_2 is then

$$y_2 = 1000(0.83)^{6.64} = \$290$$

We see that the learning curve is a useful technique in predicting costs in a mass production situation. A manufacturer considering new production equipment will certainly want to use the learning curve in reducing costs so that volume can be increased, which in turn will tend to reduce costs even more. Costs will not decrease as uniformly as Fig. 2 would suggest, but in small steps as new manufacturing equipment is brought into service, with the overall effect approximating a straight line.

Once the costs of a given machine are determined, they must be described to others in understandable terms. The cost of a wind machine can be described in at least four ways: by *total cost*, *cost per unit area*, *cost per kW of rating*, and the *unit cost of electricity*.

The *total cost* will be given by C_t. C_t for small machines may just refer to hardware shipped from the factory, but C_t for the large machines will almost always include land, access roads, distribution lines, and construction. The latter should be included whenever possible to give a more accurate economic picture. C_t does not include operating or maintenance costs, which are treated separately.

The cost per unit area would be

$$C_a = \frac{C_t}{A} \qquad \$/\mathrm{m}^2 \tag{7}$$

where A is the projected area of the turbine in m^2. C_a can be used to compare turbines of different types, different sizes, and different rated wind speeds. Plant factor or capacity factor as described in Chapter 4 would also need to be specified before any intelligent purchase decisions could be made.

A measure of cost which is widely used is the *cost per kW* of rating,

$$C_{\mathrm{kW}} = \frac{C_t}{P_{eR}} \qquad \$/\mathrm{kW} \tag{8}$$

where P_{eR} is the maximum or rated electrical power output of the wind machine. This is the measure commonly used by the utility industry for other types of generation, hence fits naturally into the thinking of many people.

Unfortunately, the measure C_{kW} is not a particularly good measure of cost for wind machines. A machine rated at 100 kW in a 8 m/s wind speed could be rated at 200 kW in a 10 m/s wind speed by just doubling the rating of the generator and the electrical wiring. Electrical equipment is a small part of the total cost, so this change in rating may be accomplished for only a few percent change in C_t. If C_t is \$100,000 for the 100 kW machine and \$102,000 for the 200 kW machine, C_{kW} would drop from \$1000/kW to \$510/kW. But, as we saw in Chapter 4, the capacity factor will drop significantly in making this change, so the total yearly energy production may not increase much and may even decrease from this change in rating. Therefore, C_{kW} may be very misleading. It should be used with care, preferably only when capacity factor can also be specified.

Yet another measure of cost, which is really the most important one, is the *unit cost of electricity*,

$$C_u = \frac{A_n}{W} \qquad \$/\mathrm{kWh} \tag{9}$$

where A_n (not to be confused with area A) is the annual cost of W kilowatthours of electricity. W is the net electrical energy produced per year per kW of rating. C_u can represent either busbar, wholesale, or retail costs. *Busbar* would be the cost at the generating plant, without including costs of transmission and distribution. *Wholesale* would be the price to another electric utility, including costs of transmission. *Retail* is the price to a given class of customer as determined by the regulatory agency, and which may not exactly reflect production costs. In this chapter C_u is normally assumed to be the busbar cost.

2 ECONOMIC CONCEPTS

In order to discuss the costs of wind generating plants and conventional generation further, we must develop some economic concepts. These concepts are developed in more detail in texts on engineering economics[12].

One very important concept is that of *present value* or *present worth*. The present value P_v of a *uniform series* of end of period payments A_n at *interest rate* i lasting for n periods is

$$P_v = A_n \frac{(1+i)^n - 1}{i(1+i)^n} \tag{10}$$

The present value P_v and the series of payments A_n are said to be equivalent in an economic sense. The money is equivalent whether being borrowed or loaned and whether payments are being made or collected. This process is illustrated in Fig. 3. The present value is the value at time 0 or *Year 0*, with equal payments being made at the end of each period. If the period is one year, then the first payment occurs at the end of Year 1, and similarly for the remainder of the n years.

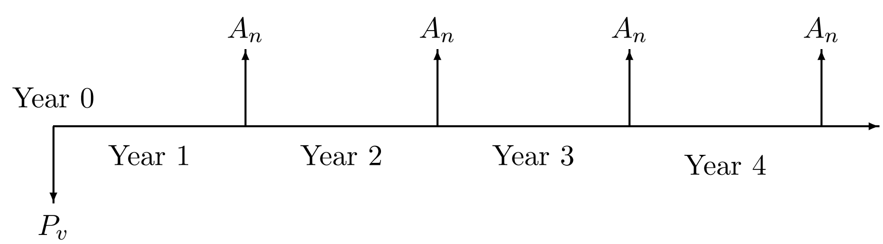

Figure 3: Present value of uniform series of end-of-period payments.

Example

What is the present value of a yearly payment of \$100 for 20 years if the interest rate is 12 percent?

$$P_v = 100 \left[\frac{(1+0.12)^{20} - 1}{0.12(1+0.12)^{20}} \right] = \$746.94$$

The total paid out is \$100(20) = \$2000, but this is not the present value because we do not have to spend the entire sum now. We can think of the process as putting a smaller sum of money in the bank at some interest rate, and then withdrawing part of the original sum plus interest to make the necessary payment. In fact, if \$746.94 is placed in the bank at 12 per cent interest compounded yearly, and \$100 is withdrawn at the end of each year, the account will just reach zero at the end of 20 years. The series of yearly payments of \$100 is considered equivalent to \$746.94 in hand now for economic analysis purposes.

Example

An Enertech 4000 reaches a maximum power of 4.2 kW in an 11-m/s wind speed. The propeller diameter is 6 m. The installed cost at your location is \$10,000 in 1981. You estimate the Weibull parameters at your site to be $c = 8$ m/s and $k = 2.2$. The interest rate is 0.11 and the period of the loan or the desired payback period is 15 years. Find C_a, C_{kW}, and C_u. Do not include factors such as tax credits, inflation, or operation and maintenance costs.

The area is

$$A = \frac{\pi d^2}{4} = \frac{\pi(6)^2}{4} = 28.27 \ \text{m}^2$$

The cost per unit area is then

$$C_a = \frac{C_t}{A} = \frac{10,000}{28.27} = \$354/\text{m}^2$$

The cost per kW is

$$C_{\text{kW}} = \frac{10,000}{4.2} = \$2380/\text{kW}$$

We need the total yearly energy production W to find the unit cost of electricity. We go back to Chapter 4 and find the capacity factor CF = 0.380. The yearly energy production is then

$$W = P_{eR}(\text{CF})(\text{hours/year}) = (4.2)(0.380)(8760) = 13,980 \ \text{kWh}$$

The annual payment A_n is found from Eq. 10.

$$A_n = \frac{10,000}{\dfrac{(1.11)^{15} - 1}{0.11(1.11)^{15}}} = \$1390.65$$

The unit cost of electricity is then

$$C_u = \frac{A_n}{W} = \frac{\$1390.65}{13,980} = \$0.099/\text{kWh}$$

We shall see in later examples that this figure is somewhat higher than the unit cost of coal generated electricity from new coal plants. This means that the installed cost must be significantly reduced before wind machines of this size can displace conventional coal fired generation.

Example

You wish to buy a house and need to borrow $50,000 to pay for it. The local Savings and Loan Company offers you the money at 15 percent interest per year to be paid back in equal monthly payments over a 20 year period. What is the monthly payment?

The number of periods is $n = (20)(12) = 240$. The yearly interest rate must be adjusted to this monthly period. The monthly interest rate will be $i = 15/12 = 1.25$ percent per month. Equation 10 can then be solved for A_n.

$$A_n = \frac{50,000}{\frac{(1.0125)^{240} - 1}{0.0125(1.0125)^{240}}} = \frac{50,000}{75.94} = \$658.39$$

The total amount that will be paid back to the Savings and Loan will be (658.39)(240) = $158,014.75 so the total interest paid would be $108,014.75 or a little more than twice the amount originally borrowed.

The preceding present worth analysis does not yield all the desired information during times of inflation. Our utility bills tend to go up each year even when our energy consumption does not go up. We are then faced with the desire to determine the present worth of a series of annual payments which increase each year. The yearly increase depends on both the general inflation being experienced in the nation and the change in cost of the particular item relative to the general inflation. Oil, for example, increased in price more rapidly than the rate of general inflation between 1973 and 1979. The annual rate of increase in a cost in terms of constant dollars is called the *real escalation rate* e_r. Real escalation results from resource depletion, increased demand with limited supply, etc.

When the real escalation is combined with the *general inflation rate* e_i, we get the *apparent escalation rate* e_a. The relationship among these quantities is

$$1 + e_a = (1 + e_r)(1 + e_i) \tag{11}$$

In some situations, such as some product being on the learning curve, or a part of a long term, fixed price contract, the real escalation may be negative. If the real escalation of hand-held calculators is -0.1 in a time when inflation is 0.14, the apparent escalation would be (1 - 0.1)(1 + 0.14) - 1 = 0.026. That is, with this negative real escalation, hand-held calculators would be increasing in price at 2.6 percent per year (apparent escalation) while prices of other products are increasing at an average rate of 14 percent per year.

Interest rates are also affected by inflation, tending to be somewhat above the general rate of inflation. Long term data in the power industry suggests that the interest rates have averaged about 4 percent above the inflation rate. For example, if the inflation rate is 6 percent, the interest rate averages about 10 percent. One can then define an *apparent interest rate* i_a as the following function of the actual interest i and the apparent escalation e_a.

$$i_a = \frac{1+i}{1+e_a} - 1 \tag{12}$$

A dollar placed in the bank at interest i will yield $1+i$ dollars a year later. However, these *Year 1* dollars are not worth as much as *Year 0* dollars because of inflation. The $1+i$ Year 1 dollars are actually worth $1+i_a$ Year 0 dollars. Year 0 dollars are sometimes called *constant dollars* while Year 1, Year 2, etc. dollars would be *current dollars*. All economic studies need to be expressed in constant dollars whenever possible so that economic decisions can be based on consistent data.

The *future value* F (in current or Year n dollars) of a present value P_v placed in a bank at interest i is

$$F = P_v(1+i)^n \tag{13}$$

The present worth of a single sum of money F to be paid at Year n with interest i is

$$P_v = \frac{F}{(1+i)^n} \tag{14}$$

Suppose now we want to determine the present worth of an uniform series of payments when the inflation rate is e_i and the real escalation is zero. When expressed in constant dollars, the annual payments look like those shown in Fig. 4. Using Eq. 14 and a summation, the present value of the series would be

$$\begin{aligned} P_v &= \sum_{j=1}^{n} \frac{A_n}{(1+e_a)^j(1+i)^j} \\ &= A_n \frac{(1+e_a)^n(1+i)^n - 1}{(e_a+i+e_a i)(1+e_a)^n(1+i)^n} \end{aligned} \tag{15}$$

Example:

What is the present value of a yearly payment of \$100 for 20 years if the interest rate is 12 percent and the apparent escalation rate is 9 percent?

$$P_v = 100\left[\frac{(1+0.09)^{20}(1+0.12)^{20} - 1}{[0.09+0.12+(0.09)(0.12)](1+0.09)^{20}(1+0.12)^{20}}\right] = \$444.52$$

This is a substantially lower value than obtained in the previous example where inflation was not considered. The person who borrows the present value of the previous example, \$746.94, and pays it

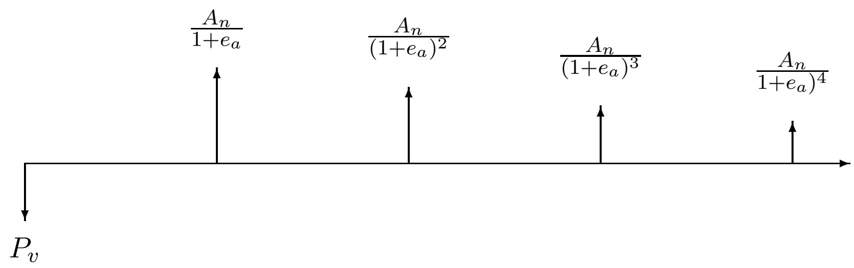

Figure 4: Present value of uniform series of payments when apparent escalation is equal to inflation rate.

back with one hundred deflating dollars each year for 20 years is actually gaining the difference of the present values. He borrows \$746.94 and pays back the equivalent of \$444.52, so he gains \$302.42.

Now we want to determine the present value of an *uniformly escalating* series of payments. These might be for a fixed amount of fuel or energy each year, with the cost increasing at the apparent escalation rate e_a. Each years payment is higher than the previous years payment by the factor $1+e_a$. The series is shown in Fig. 5. The present value of this series is given by:

$$P_v = \sum_{j=1}^{n} \frac{A_n(1+e_a)^j}{(1+i)^j} = A_n(1+e_a)\frac{\left(\frac{1+e_a}{1+i}\right)^n - 1}{e_a - i} \tag{16}$$

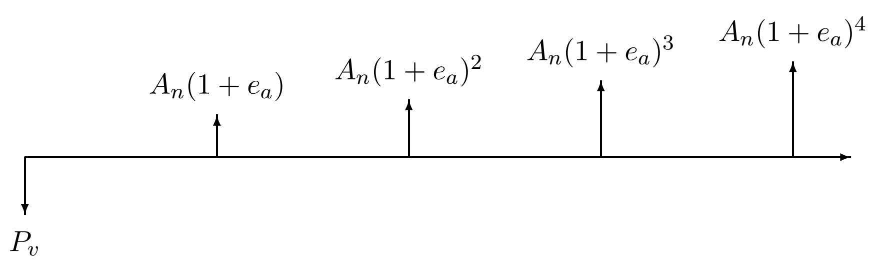

Figure 5: Present value of a series of annual payments increasing at the apparent escalation rate e_a.

Example

You are considering adding some insulation in your home which should save you 1200 kWh of electricity per year. If electricity costs \$0.05 per kWh with an apparent escalation rate of 8 percent, what is the present value of 20 years of payments for this electricity? Assume interest rates are 12 percent.

The Year 0 cost, A_n, of 1200 kWh is 1200(0.05) = \$60. When we substitute this in Eq. 16 we get:

$$P_v = 60(1+0.08)\frac{\left(\frac{1.08}{1.12}\right)^{20} - 1}{0.08 - 0.12} = \$837.24$$

If the insulation costs less than \$837.24 it would be economically acceptable to buy the insulation. If it costs more, then other conservation schemes need to be examined. Of course, uncertainties about escalation and interest rates will cause many small investors to buy the insulation even when the present economic conditions make the purchase economically marginal.

Equations 15 and 16 are easily confused because they contain the same parameters. The difference is that Eq. 15 applies to an *uniform* series and Eq. 16 to an *uniformly escalating* series. In one case the number of current dollars is fixed, while in the other case, the number of current dollars increases each year.

We can always compare economic alternatives by examining the present value of each alternative. However, it is also desirable to compare alternatives by comparing annual costs. We like to know what our monthly or yearly payment will be. The variable annual costs due to escalation makes this comparison difficult, if starting dates and expected plant lifetimes are different. This difficulty is overcome by defining an *equivalent levelized end-of-year cost* L as[11]

$$L = P_v \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{17}$$

The expression in the brackets is called the *capital recovery factor*. The levelized cost is determined by first finding the present value P_v for the actual escalating series of payments, such as Eq. 16. Then Eq. 10, which applies to an uniform series of payments, is solved for the annual payment A_n. This annual payment is renamed L to indicate its levelized nature.

Another term which is often used in such economic studies is the *levelizing factor*[3] LF where:

$$\mathrm{LF} = \frac{L}{A_n} = (1+e_a)\frac{\left(\frac{1+e_a}{1+i}\right)^n - 1}{e_a - i}\frac{i(1+i)^n}{(1+i)^n - 1} \tag{18}$$

A_n is the actual Year 0 annual cost. The levelizing factor will remain constant for a given set of economic assumptions, and therefore provides a convenient means of determining the levelized costs when the first year costs are known.

Example:

Determine the levelized cost and the levelizing factor for the electricity costs of the previous example.

Substituting the present value of \$837.24 into Eq. 17 yields

$$L = (837.24)\frac{0.12(1.12)^{20}}{(1.12)^{20} - 1} = \$112.09$$

$$\text{LF} = \frac{112.09}{60} = 1.868$$

The yearly electricity bill after 20 years is $60(1.08)^{20} = \$279.66$. The levelized annual cost of \$112.09 is equivalent to the series of actual annual costs which increase from \$60 to \$279.66. The levelized cost of electricity over this period would be just the levelizing factor times the current cost, or $(0.05)(1.868) = \$0.0934$/kWh.

3 REVENUE REQUIREMENTS

Wind generators connected to the utility grid may not be owned by the utility but can still be treated by basically the same economic analysis. Different ownership may change the interest rates or the tax status, but the same analysis procedure still applies. We shall, therefore, examine the revenue requirements of the electric utility industry in general, and then specialize our results to wind generators.

The electric utility industry has five unique characteristics that set it apart from other industries[3]:

1. The industry is capital intensive. For a given utility, over half of the revenue from the sale of electricity may be allocated to sustain the capital investment. An even greater fraction is required for generation without fuel costs, such as wind.
2. The industry's investment items generally are long-lived, often in the range 30 to 40 years.
3. The industry has a relatively constant flow of revenue dollars on an annual basis compared to other industries.
4. The industry's product demand and usage is determined by the customer.
5. The industry is mandated to provide reliable, low-cost, environmentally acceptable electricity and for the most part is regulated by government agencies.

These characteristics make the revenue requirement approach to economic studies the most logical of the possible techniques. In this approach, the revenue that would be required to sustain a given alternative is determined and compared to a similarly derived revenue of every other alternative. This method determines the revenue required from the utility customers and the *rates* for electricity they must pay, and therefore helps the regulators in their role of insuring an adequate electricity supply at the lowest possible cost.

Revenue requirements consist of two components, *fixed costs* and *variable costs*, as illustrated in Fig. 6. Fixed costs include debt repayment, depreciation, income taxes, property taxes, and insurance. Variable costs include fuel, operating, and maintenance costs. Utilities do not usually pay for generating plants from current revenue because it would require present customers to pay for items which would benefit other customers as much as 40 years into the future and because the relatively constant revenue dollars would not normally be adequate to pay for a construction program that may vary widely through time.

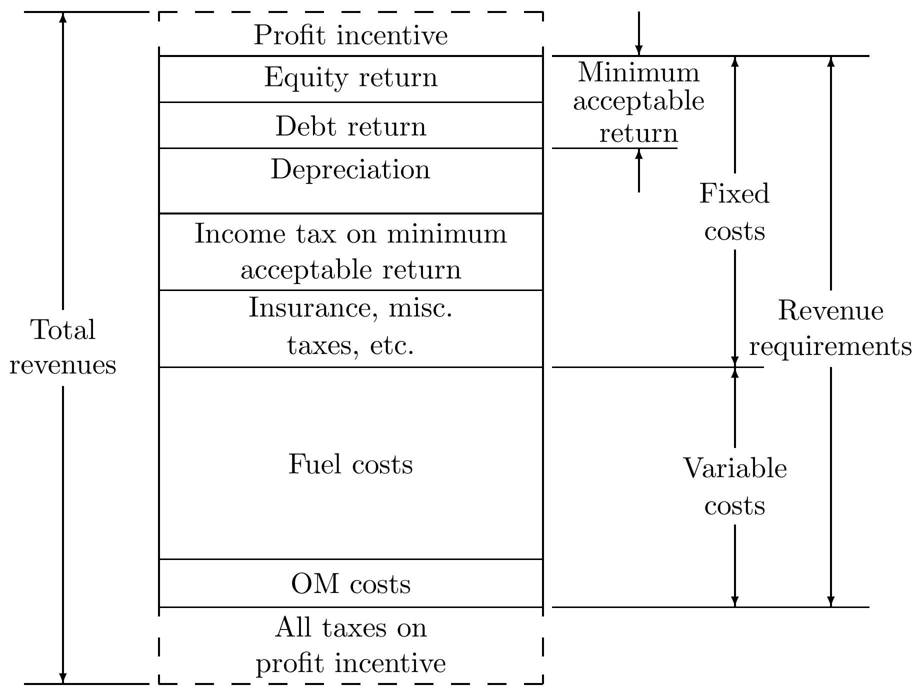

Figure 6: Revenue requirements on investment.

The cost of a new generating plant, therefore, comes from new financing through the sale of bonds and debentures referred to as *debt financing* and from the sale of common and preferred stock, referred to as *equity financing*. The return (the money that the utility must pay for the use of both debt and equity money) is allowed as a revenue requirement for rate-making purposes and is a part of the fixed cost associated with an investment. The other components of the fixed costs include *book depreciation* (an annual charge to repay the original amount obtained from investors), Federal and local income taxes, property taxes, and insurance.

Figure 6 also shows a segment entitled *Minimum Acceptable Return* that is equal to debt and equity return. This is the lowest amount that investors will accept to provide the funds needed by the utility to make the investment. It should also be noted that total revenues must be greater than revenue requirements. The difference is an additional profit incentive.

It and associated taxes are needed to attract investors.

Revenue requirements tend to increase with time because of inflation, but are irregular because of variations in such items as maintenance. These are normally levelized to make the task of comparing alternatives easier. The levelized annual revenue requirements consist of the levelized annual fixed costs and the levelized annual variable costs. In equation form,

$$L = L_f + L_v \qquad \$/\text{kW/year} \tag{19}$$

The levelized annual fixed costs can all be expressed as percentages of the initial capital investment. Typical percentages for a coal generating plant with a 30 year expected life, 6 percent inflation, and 10 percent weighted cost of capital (average interest) are: 10 percent for interest, 1.17 percent for depreciation and retirement dispersion, 4.7 percent for income taxes, and 2 percent for property taxes and insurance[3]. The total is 17.87 percent, which is then normally rounded to 18 percent for discussion purposes. Retirement dispersion is an economic allowance for the fact that actual power plant retirements do not coincide exactly with the initial assumed lifetime, but rather are dispersed around some average lifetime. This requires an adjustment to the depreciation allowance.

This percentage of initial capital investment is called the *levelized annual fixed charge rate*, r_f, or simply the *fixed charge rate*. Depreciation is a small fraction of the fixed charge rate for plants with long lives, so the same fixed charge rate is normally used for plants with expected lives of 25 years or more. The fixed charge rate would be greater for shorter lived plants, typically 23 percent for a 10 year life and 34 percent for a 5 year life[3]. Tax benefits such as the investment tax credit would lower the fixed charge rate.

Unless there is preferential tax treatment for wind generators, the fixed charge rate for utility owned wind turbines will have to be very close to the fixed charge rate for conventional generation. Even if wind machines are privately owned by other groups, the fixed charge rate would probably be quite similar to what it would be if the utilities owned the machines. Any group that owns substantial amounts of generation will be viewed as an utility by investors, and may even be regulated by the local regulatory agency. This allows us to estimate a fixed charge rate for wind machines and thereby quickly determine the fixed cost portion of the cost of electricity produced.

Example:

A wind turbine with a cost of \$800/kW and a capacity factor of 0.3 has a fixed charge rate r_f of 18 percent. What is the fixed charge portion of electric energy costs from this turbine?

The yearly energy produced per kW of rating is

$$W = 8760(0.3) = 2628 \ \text{kWh}$$

The annual fixed charge is

$$L_f = 800(0.18) = \$144/\text{kW}$$

The unit cost of electricity due to this fixed charge rate is then

$$C_{uf} = \frac{L_f}{W} = \frac{144}{2628} = \$0.0548/\text{kWh}$$

Variable costs in Fig. 6 consist of *fuel costs* (if any) plus *operation and maintenance* (OM) costs. The OM costs consist of both a fixed and a variable portion. The fixed portion is defined as being invariable with energy generated, transferred, or used. The variable portion depends on the amount of generated power. This would include water, limestone, filter bags, and ash disposal costs for coal generators. Wind generators do not consume anything as they generate electricity, but some maintenance functions will depend on the number of hours of operation, so these functions would represent the variable portion. The variable costs are normally expressed in mills/kWh, where 1 mill = $0.001 or one tenth of a cent. The fixed OM costs are expressed in dollars per year per kW of rating. The levelized annual variable costs would then be expressed as

$$L_v = L_{\text{fuel}} + L_{\text{fom}} + L_{\text{vom}} \qquad \$/\text{kW/yr} \tag{20}$$

where L_{fuel} is the levelized annual fuel cost, L_{fom} is the fixed OM cost, and L_{vom} is the variable OM cost.

We see that the levelized annual fuel cost L_{fuel} is just the present cost of fuel to generate one kWh, C_{fuel}, times the number of kWh generated per year by each kW of capacity times the levelizing factor.

$$L_{\text{fuel}} = (C_{\text{fuel}})(W)(\text{LF}) \qquad \$/\text{kW/yr} \tag{21}$$

We may also define the levelized annual revenue requirements in dollars per kWh L' rather than the dollars per year per kW of capacity L.

$$L' = \frac{L}{W} \tag{22}$$

Similar expressions hold for the individual components of L, L_f and L_v.

We now want to present a major example of all these computations for a large coal plant. These numbers were developed for the Electric Power Research Institute[3] and thus represent typical utility values for end-of-year 1978.

Example

A large coal plant has the following data assumptions:

Plant cost, C_{kW}	\$900/kW
Levelized fixed charge rate, r_f	0.18
Levelized capacity factor	0.68
Fuel cost	\$0.95/10^6 Btu
Heat rate	10,000 Btu/kWh
Fixed OM costs (year 0)	\$3.00/kW/year
Variable OM costs (year 0)	1.10 mills/kWh
Inflation	0.06/year
Cost of capital	0.10
Startup date	End-of-year 1978
Plant Life	30 years

1. Find the levelized annual fixed costs per kWh.
2. Find the levelized annual variable costs per kWh.
3. Find the present worth of the fuel per kW of plant rating.
4. Find the levelized annual busbar cost of electricity.

The fixed cost per kW of rating is just

$$L_f = C_{\mathrm{kW}} r_f = 900(0.18) = \$162.00/\mathrm{kW}$$

The energy produced per year per kW of rating is

$$W = (8760)(0.68) = 5957 \ \ \mathrm{kWh}$$

The levelized fixed cost per kWh is then

$$L_f' = \frac{L_f}{W} = \frac{162}{5957} = \$0.0272/\mathrm{kWh} = 27.2 \ \ \mathrm{mills/kWh}$$

The fuel cost in Year 0 dollars is

$$C_{\mathrm{fuel}} = (\$0.95/10^6 \ \ \mathrm{Btu})(0.01 \times 10^6 \ \mathrm{Btu/kWh}) = 9.5 \ \ \mathrm{mills/kWh}$$

The levelizing factor is, from Eq. 18,

$$\mathrm{LF} = (1.06)\frac{\left(\frac{1.06}{1.10}\right)^{30} - 1}{0.06 - 0.1}\,\frac{0.1(1.1)^{30}}{(1.1)^{30} - 1} = 1.886$$

The levelized annual fuel cost is

$$L_{\mathrm{fuel}} = (0.0095)(5957)(1.886) = \$106.73/\mathrm{kW/yr}$$

Expressed in mills per kWh, this is

$$L'_{\text{fuel}} = (9.5)(1.886) = 17.92 \text{ mills/kWh}$$

The present value of the fuel consumed for each kW of rating is, from Eq. 17,

$$P_v = \frac{106.73}{\frac{0.1(1.1)^{30}}{(1.1)^{30} - 1}} = \$1006.13/\text{kW}$$

The OM costs are

$$L'_{\text{fom}} = \frac{\$3.00}{5957}(1.886) = 0.95 \text{ mill/kWh}$$

$$L'_{\text{vom}} = (1.10)(1.886) = 2.07 \text{ mills/kWh}$$

The total levelized cost per kWh is then

$$L' = 27.2 + 17.92 + 0.95 + 2.07 = 48.14 \text{ mills/kWh}$$

The present worth of the coal is actually greater than the present worth of the plant. However, the revenue requirements necessary for the coal are less than for the plant because expenses such as profit and taxes are not allocated to the fuel.

4 VALUE OF WIND GENERATED ELECTRICITY

We have shown that wind generated electricity has value both from capacity displacement of conventional generation and from saving fuel. A capacity credit can only be given if the construction of the wind turbine actually prevented some conventional generation from being built. The fuel savings mode can always be applied, even when conventional generation is not affected.

Utility companies are faced with many options when planning new generation. Two of the more common options would be to use wind generation to displace new coal generation or to save oil at existing oil fired units. New oil fired units are not being built because of fuel costs, so wind generation cannot displace these. If wind generation is displacing coal generation, then it cannot save oil at the same time. Both options need to be examined by the utility.

We shall now illustrate the use of the various economic tools which have been developed by two lengthy examples. We basically want to know if wind generation is economically competitive with either new coal construction or existing oil generation.

Example

Wind turbines are available to an utility at \$700/kW. The estimated capacity factor is 0.35 and the effective capacity is 0.4. The fixed charge rate is 18 percent, interest is 10 percent, and apparent escalation is 6 percent. Expected operating life time is 30 years. The wind turbines would be used to displace coal generation with the parameters detailed in the example at the end of Section 8.3. This coal generation is assumed to have an effective capacity of 0.76. The OM costs of the wind generators are arbitrarily assumed to be the same as those for coal.

What is the change in revenue requirements involved in replacing 100 MW of coal generation with wind generation?

From Eq. 66 in Chap. 5, the rated power of the wind generators would be

$$P_{\rm eR} = \frac{D_c E_c}{E_w} = \frac{100,000(0.76)}{0.4} = 190,000 \text{ kW}$$

The energy produced by this much wind generation per year would be

$$W_w = (190,000)(0.35)(8760) = 582.5 \times 10^6 \text{ kWh}$$

The energy produced by the 100 MW of coal generation displaced would be

$$W_c = (100,000)(0.68)(8760) = 595.7 \times 10^6 \text{ kWh}$$

The 190 MW of wind generators yield the same power system reliability as 100 MW of coal generation, but the energy production is not as much. We will assume that this energy deficit can be made up by operating other coal plants at a slightly higher plant factor. We will further assume that the appropriate cost per kWh is just the fuel and variable OM costs of the other coal plants since fixed costs have already been justified for these plants. Other assumptions may be better, depending on the particular situation of the utility, but this assumption should be adequate for this relatively small deficit.

The levelized fixed yearly cost for the wind generators is

$$L_f = 700(0.18) = \$126/\text{kW}$$

The energy production per kW of rating is

$$W = (8760)(0.35) = 3066 \text{ kWh}$$

The fixed cost per kWh is then

$$L'_f = \frac{126}{3066} = \$0.0411/\text{kWh} = 41.1 \text{ mills/kWh}$$

The OM costs are

$$L'_{\rm fom} = \frac{\$3.00}{3066}(1.866) = 1.85 \text{ mills/kWh}$$

$$L'_{\text{vom}} = (1.10)(1.866) = 2.07 \text{ mills/kWh}$$

The extra cost of the energy deficit would be the sum of the fuel cost and variable OM cost of coal generation times the total energy.

$$C = (17.92 + 2.07 \text{ mills/kWh})(595.7 - 582.5) \times 10^6 \text{ kWh} = \$263,900$$

This cost is then spread over all the wind generated kWh to find the levelized cost per kWh.

$$L'_{\text{def}} = \frac{263,900}{582.5 \times 10^6} = 0.45 \text{ mill/kWh}$$

The total levelized busbar wind energy cost per kWh is then

$$L' = 41.1 + 1.85 + 2.07 + 0.45 = 45.47 \text{ mills/kWh}$$

The levelized energy cost of the wind machines is less than that of the equivalent coal generation by 2.67 mills/kWh, therefore the economic choice is wind machines, at least in this particular case.

Example

A municipal utility is entirely supplied by diesel generators. The heat content of the diesel fuel is 146,000 Btu/gallon and the heat rate is 11,500 Btu/kWh. Diesel fuel costs \$1.40/gallon and has an apparent escalation rate of 8 percent while the general inflation rate is 6 percent.

Should the municipal utility buy wind machines as fuel savers? Assume the same parameters as in the previous example.

The cost of the wind generated electricity would be the same as the previous example except for the small charge for extra coal. That is,

$$L' = 45.47 - 0.45 = 45.02 \text{ mills/kWh}$$

From Eq. 23 in Chap. 7, the present fuel cost per kWh is

$$C_{\text{fuel}} = \frac{\$1.40/\text{gal}}{146,000 \text{ Btu/gal}}(11,500\text{Btu/kWh}) = 110.3 \text{ mills/kWh}$$

From Eq. 18, with an apparent escalation of 8 percent and an interest rate of 10 percent, the levelizing factor is

$$\text{LF} = (1.08)\frac{\left(\frac{1.08}{1.10}\right)^{30} - 1}{0.08 - 0.10}\frac{0.10(1.10)^{30}}{(1.10)^{30} - 1} = 2.425$$

The levelized cost of oil per kWh is then

$$L'_{\text{oil}} = 110.3(2.425) = 267.48 \text{ mills/kWh}$$

The levelized cost of oil is five times that of wind generated electricity for this set of numbers. This shows that fuel savings may be much better than capacity credit when the fuel being saved is oil and the capacity credit can only be applied to new coal construction. It also shows that oil fired generation should be used as sparingly as possible, ideally only in emergencies.

5 HIDDEN COSTS AND NONECONOMIC FACTORS IN INDUSTRIALIZED NATIONS

We have developed methodology to make simple economic evaluations of wind generators and conventional generation. More detailed models are used by utilities, but this methodology shows at least the main effects of initial investment, fuel costs, operation and maintenance costs, and inflation on both the cost and value of wind generated electricity. There are other factors besides the ones normally found in economic studies which will affect the deployment of wind turbines and it seems appropriate to mention some of these factors here.

It should be noted that wind generated electricity does not have hidden costs to society. Coal plants require the mining and transportation of large quantities of coal, with the problems of strip mine reclamation and polluted water supplies in the producing states. The burning coal adds rather large quantities of carbon dioxide and sulfur dioxide to the atmosphere, with possible serious consequences to the earth's climate and food producing capability. Nuclear power has enjoyed the benefit of massive government sponsored research and development efforts, the costs of which are not reflected in the normal economic studies. The costs of nuclear waste disposal and cleanup costs of a nuclear accident have historically not been fully included in economic evaluations. These hidden costs are difficult, if not impossible, to quantify, but will surely play a role in the deployment of wind generators because they tend to favor wind generation in the political arena. When the normally assigned costs are about the same, the decision makers will probably decide for wind generation to minimize these hidden costs.

Political action can also affect the results of these economic studies. Artificially low interest rate, long term loans can make economically marginal wind generation economically superior at the stroke of a pen. This makes economic forecasting a hazardous business. For example, the little booklet *Electric Energy from Winds*, written in 1939 but not published until 1946, contains the following statement[10]: "There are many rural areas in our midwest where the farms are so far apart that it probably will never be economically justifiable to supply electric power from transmission lines."

The Rural Electrification Act of 1936 made it possible for almost every farm in the midwest to be tied to a transmission line by 1955. Political action rendered the prophecy incorrect even before it got into print.

Two other factors which affect the economics of wind power are the strong developmental efforts being made in energy storage and load management. Utilities are working to replace peaking oil fired generation with base loaded coal or nuclear generation. Energy storage, such as pumped hydroelectric, batteries, or even flywheels, would supply the peak loads and then be recharged during off peak times. Load management will shift loads, such as domestic hot water heaters, from peak times to non peak times. If storage and load management equipment expand to represent a substantial fraction of the total installed generation capacity, then oil fired peaking equipment would be used only for emergencies. Oil would be burned only when conventional generation is on forced outage. In such a system, conventional generation will tend to supply the average load rather than the peak load. Peak loads are shifted to a later, non peak time by load management and are partly met by storage which is refilled during offpeak times.

Wind power would augment such a system very nicely. It would act as an energy supplier along with the conventional generation. If the wind did not blow during peak load times, more energy would be drawn from storage and more loads would be delayed to a later time. If conventional generation, storage, and load management were unable to meet the load, then some oil fired generation would be used.

One other factor needs to be mentioned. This is the possibility that fuel supplies for existing conventional generation may not be adequate to meet the demand. Some combination of oil imports being shut off, coal barges frozen in the Ohio River, coal miners on strike, and nuclear fuel unavailable would mean that not enough electricity could be produced to meet the demand, even though the generating plants are otherwise operational. Wind generators would be able to at least reduce the number and severity of the rotating blackouts. Schools and industry may be able to continue operation during the times when the wind is blowing and thus reduce the impact of such fuel shortfalls. The electricity produced during such periods would have substantially greater value to society than the electricity produced in a fuel saver mode. Wind generators may be considered as somewhat of an insurance policy against serious fuel supply problems.

These factors all tend to favor wind generation over conventional generation. If wind systems are about equal to conventional generation on a purely economic basis, then it would seem that the noneconomic factors would tip the scales in favor of wind generation.

6 ECONOMIC AND NONECONOMIC FACTORS IN DEVELOPING COUNTRIES

There are nearly one billion people living in scattered rural areas of developing countries in the continents of Asia, Africa, and South America who have very poor living conditions. These conditions are encouraging a massive exodus to the urban slums, which makes the overall situation even worse in many cases. Most of the developing countries are poor in conventional fossil fuel resources and have to import them with their meager foreign exchange reserves. There appear to be only two technically feasible solutions to their energy problems. One is a commitment to large central nuclear power plants and a power transmission and distribution network. The other is a decentralized system of solar and wind equipment installed at the village level. There are many people[14] who believe that the latter solution is the best and may be the only solution that is politically feasible.

The energy needs of small rural communities fall into three categories: energy to improve living conditions, energy to improve agricultural productivity, and energy for small-scale industries. It is difficult to set priorities among these needs, but living conditions certainly have to be improved if the people are to have any hope in the future. Comparatively small amounts of energy could meet the basic needs for cooking of food, pumping and purifying drinking water, and lighting of dwellings. Once these needs are met, work can begin on increasing agricultural and industrial productivity.

A rough estimate of the energy needs of a typical village of 200 families is as follows[1]: 88,000 kWh per year for cooking food, 1,000 kWh per year for pumping water, and 26,000 kWh per year for lighting. This averages 315 kWh per day, most of which must be supplied during a three hour period in the evening. The energy required for cooking food is about three-fourths of the total, and any workable system must be able to satisfy the load even if all the villagers choose to cook at the same time. The most obvious solution is a diesel engine and a 100-kW or 150-kW generator, but the cost of fuel makes this unacceptable. This energy use pattern also puts some difficult constraints on any solar or wind systems which might be used. The output of a solar collector will be near zero by the time of the peak load and the wind may be calm at that time also. Storage adequate to meet at last one days load is, therefore, essential. This storage would be in the form of storage batteries for wind and solar electric systems.

Another possibility for the energy system is biogas. Plant, animal, and human wastes can be used to produce methane, which can be stored and used directly for cooking. It is inefficient to use methane directly for lighting so the methane can be used in an internal combustion engine driving an electrical generator to provide electricity for lighting. This holds capital investment to a minimum but requires considerable labor to keep the biogas facility and the internal combustion engine operating.

Studies indicate[14, 1] that the cost of electricity in such remote locations is perhaps a factor of four times as much as the cost enjoyed by people in developed countries with large central coal and nuclear electric generating plants. Solar and wind systems are competitive with conventional systems, but all systems tend to be expensive. The actual amount of energy consumed per person is not large, so costs per kWh can be relatively high and still be acceptable. One problem is that people look at the costs of equipment, the lack of transportation, the lack of trained people, and the centuries-old traditions and customs and conclude that it is not economically feasible to supply electricity to these villages. The villages are left in poverty and hopelessness. City slums are perceived to be a better place to live, with massive migrations of people. The country becomes more unstable and ripe for revolution as this process continues. It can be argued13 that the real costs to a developing country and even to the world community of nations is greater if these basic energy needs are not met than if they are met. An improving standard of living in the rural areas would relieve a great deal of human misery and also improve the political stability of the world. As Dr. I.H. Usmani, Senior Energy Advisor, United Nations Environmental Programme, once said, "these villagers must have energy, not at a price, but at any price."

7 PROBLEMS

1. The first unit of a new line of wind turbines costs $1500 per kW. If the slope of the learning curve is $s = 0.92$, what is the estimated cost of the hundredth unit?

2. A small wind turbine manufacturer is able to sell unit number 100 for $5000. If he is on a learning curve with $s = 0.88$, what will unit number 500 cost?

3. If the second wind turbine unit built of a given model costs $1200/kW, how many units would have to be sold to get the price down to $800/kW, if the slope of the learning curve is $s = 0.86$?

4. An insulating cover for your electric hot water heater costs $30 and is claimed to save 120 kWh per year. If interest is at a 12 percent rate and the expected life of the cover is 10 years, what annual payment is equivalent to the present value of the cover? You may ignore inflation.

5. Assume for the situation in Problem 4 that electricity costs $0.05/kWh at Year 0 and has an apparent escalation rate of 6 percent. What is the present value of 120 kWh/year of electricity used for 10 years? Should you buy the cover or continue to buy the electricity?

6. What is the levelized annual cost and the levelizing factor for the electricity of Problem 5?

7. You are trying to choose between two wind machines. Machine X costs $10,000 (present value) and has estimated OM costs of $200/year, increasing each year as the apparent escalation rate, while machine Y costs $8000 with estimated OM costs of $400/year. Your bank is willing to finance either machine for 15 years at 13 percent interest. You estimate that the apparent escalation of OM costs will be 9 percent over this period. Both machines produce the same amount of energy each year. Which machine should you buy (i.e. which machine has the lowest present value of capital plus OM costs?)

8. A company offers a line of wind electric generators as shown below. You live in a region where the average wind parameters are $c = 7.5$ and $k = 2.0$. You can borrow money for 15 years at 8 percent interest. You assume an average operating and maintenance cost of 3 percent per year of capital investment. You decide to ignore inflation. Prepare a table showing the cost per unit area C_a, the cost per kW rating C_{kW}, and the unit cost of energy production for each model. You may want to use the material on capacity factor from Chapter 4.

Model	Rated Output (W)	Rated Wind Speed (m/s)	Voltage	Propeller Diameter (m)	Cost
A	1200	10.3	dc	3.0	$1695
B	1800	10.7	dc	3.5	$1940
C	2500	11.2	dc	3.8	$2380
D	4000	10.7	dc	4.4	$2750
E	6000	13.4	dc	5.0	$3275
F	1200	10.3	ac, single-phase	3.0	$2045
G	2000	11.2	ac, single-phase	3.5	$2475
H	3500	10.3	ac, three-phase	4.2	$3450
I	5000	10.3	ac, three-phase	5.0	$3840

9. You can buy a truck with a diesel engine for $500 more than the identical truck with a gasoline engine. You estimate you will get 25 miles per gallon with the diesel engine and 20 miles per gallon with the gasoline engine. Both gasoline and No. 1 diesel oil sell for $1.50 per gallon at the present time and you estimate a real escalation rate of 0.08 over the next several years. You hope to drive the truck 100,000 miles during the next seven years with no difference in maintenance costs between the cars. If inflation is 0.10 per year and interest is 0.14 per year, determine the present worth of the diesel oil and gasoline needed over the seven year period. Which truck is the economical choice?

10. A utility is considering installing a number of wind turbines with a total rating of 1000 MW in its service area. The assumed capacity factor is 0.32 and the effective capacity is 0.28. These will displace a coal fired turbine with effective capacity 0.8. The coal plant costs $900/kW in Year 0 dollars and the price of coal is $1.35/10^6 Btu. Operation and maintenance costs of both the coal plant and the wind plant are $3.00/kW/year fixed costs and 1.10 mills/kWh variable costs (at year 0). The heat rate is 10,000 Btu/kWh. The levelized capacity factor of the coal plant is 0.7. The levelized fixed charge rate is 0.19, inflation is 0.07, and cost of capital is 0.11.

    The plant life of both the coal plant and the wind generator is 30 years. System reliability is to be maintained at the same level with either the wind or the coal generation. Any difference in energy production is to be obtained by burning more or less coal at other coal generating plants. How much can the utility afford to pay for the wind turbines?

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