

Wind Energy Costs

This paper reviews the measures of cost used for electricity-generating systems employing wind turbines. Wind turbines are used in a variety of contexts and installation scales. These range from arrays of large numbers of interconnected wind turbines delivering their electricity to the utility grid (windfarms) to small clusters of machines that may or may not be connected to the grid. Wind system performance characteristics and the range of applications are explored in a companion issue paper, *Wind Performance Characteristics*. The costs of these renewable energy systems have decreased significantly over the past 15 years. The three methods customarily used to measure the costs and economic performance of wind turbine systems are described and illustrated with representative values. The descriptions begin with the *installed capital cost*, continue with the *specific capital cost* (the installed capital cost to generate one unit of energy per year), and end with the *cost of energy*.

The three cost measures are increasingly inclusive. The first deals only with the installed capital cost and is measured in dollars per kilowatt (kW). The specific capital cost combines the quality of the wind resource and the power generation characteristics of the wind turbine with the installed capital cost. The units of this second measure are cents per kilowatt-hour per year (kWh/year). The third measure is the most comprehensive. The life-cycle cost of energy (with units of cent/kWh) combines the installed capital cost, the quality of the wind resource (and its matching to the power generation characteristics of the wind turbine) and the levelized costs of operations and maintenance throughout the 20 to 30 year life of the wind system.

This third and most inclusive measure of cost, the life-cycle cost of energy, may be described in terms of utility revenue requirements or cost recovery accounting or, alternatively, from the profit-and-loss, cash-flow perspective of a non-regulated independent power producer. While a simplified utility perspective is employed here, the values arrived at should be approximately the same for either method. The paper closes with a summary.

Installed capital cost

The simplest of the three measures of cost for wind turbine systems is the *installed capital cost*. This measure includes all planning, equipment purchase, construction and installation costs for a turn-key wind system, ready to operate. As such this cost will include the wind turbine and tower delivered and installed at the site together with all electrical, maintenance and other supporting infrastructure.

Installed capital cost for a ready-to-operate windfarm includes all

- *Planning*
- *Equipment purchase*
- *Construction cost*
- *Installation cost*

In the case of a windfarm, the installed capital cost would include the electrical power collection system that extends from each wind turbine to the substation, the interconnect point with the utility grid. Depending on the policy and practice of the utility, the electrical system may or may not include the capital cost of the substation. If it

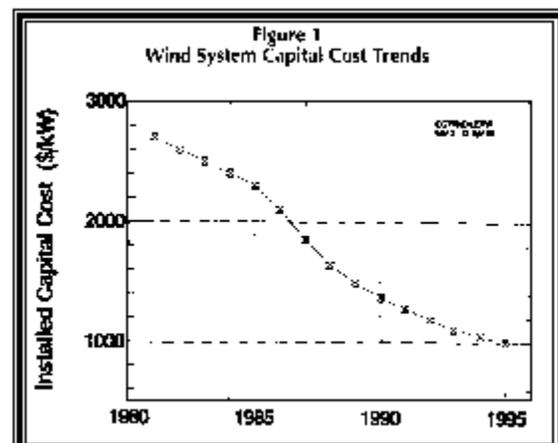
does not include the substation capital cost, there will be a lease cost or usage charge levied by the utility for providing this facility.

The installed capital cost also includes the costs of buildings in support of operations and maintenance, the initial inventory of spare parts, and maintenance and diagnostic equipment. Other included costs are the costs of preconstruction planning including wind resource assessment and analysis, surveying, permitting and the securing of financing. Depending on details of ownership and location, there may also be costs associated with negotiating land use agreements, power purchase contracts and transmission access agreements.

Thus, the windfarm installed capital cost includes the following elements:

1. Wind resource assessment and analysis
2. Permitting, surveying and financing
3. Construction of service roads
4. Construction of foundations for wind turbines, pad mount transformers and substation
5. Wind turbine and tower delivered to the site and installed
6. Construction and installation of wind speed and direction sensors together with communication capability to the associated wind turbines
7. Construction of power collection system including the power wiring from each wind turbine to the pad mount transformer and from the pad mount transformers to the substation
8. Construction of operations and maintenance facilities
9. Construction and installation of a windfarm communication system supporting control commands and data flow from each wind turbine to a central operations facility
10. Provision of power measurement and wind turbine computer control, display and data archiving facilities
11. Integration and checkout of all systems for correct operation
12. Commissioning and shakedown period
13. Final turnover to owner or operating agency

Note that the installed capital cost includes only the costs of equipment, facilities and infrastructure, ready to operate. This measure says nothing about the strength of the wind resource or the matching of the wind turbine power curve to the distribution of wind speeds. Thus the installed capital cost is not a complete measure of the economic performance of a wind system.



For windfarms, the installed capital cost has decreased from more than \$2,500/kW in the early eighties to the current range of \$900/kW to \$1,200/kW. The actual cost for a given installation depends on the size of the installation, the difficulty of construction, and the sophistication of the equipment and supporting infrastructure. For later cost illustrations, we will use the value \$1,000/kW for the installed capital cost. This value is appropriate for smaller installations. With costs continuing to go down, this value also may be appropriate for smaller installations. The capital cost trends over the last 15 years are illustrated in figure 1.

Specific capital cost

Overview

The second measure of cost combines the installed cost, the strength of the wind resource and the matching of the wind resource to the wind turbine power curve. This cost measure is called the *specific capital cost* or the unit of energy capital cost. Prior to discussing the specific capital cost, we review the factors that determine the energy production of a wind turbine. These are the technical descriptions of the wind resource, the wind turbine power curve and how they are combined to yield an estimate of the annual energy production. This will be useful for the discussion of both the specific capital cost and the life-cycle cost of energy.

Annual energy production

The annual energy production of a wind turbine depends on 1) the shape and strength of the wind resource, 2) the wind turbine power curve and 3) the degree to which they overlap. The annual energy production of a windfarm is the sum of the energy production from the component wind turbines reduced to account for various losses.

The shape and strength of the wind resource are described quantitatively by the *wind speed distribution*. The wind speed distribution gives the number of hours per year that the wind speed lies within small, adjacent wind speed intervals. The *wind turbine power curve* specifies the wind turbine's electric power output as a function of wind speed. Together, the wind speed distribution and the wind turbine power curve when multiplied together and summed over all wind speeds, provide an estimate of the wind turbine annual energy production. The wind speed distribution, the wind turbine power curve and their relationships are discussed more fully in a companion paper¹.

The annual energy production for a windfarm is always less than the summed production from the component wind turbines. There are a number of contributing loss factors. These include the array losses associated with distortion of the wind flow downstream of operating wind turbines, losses associated with the electric power collection network and departures from ideal performance of the wind turbine blades.

Wind energy system costs have decreased significantly over the last 15 years. Specific capital cost

The specific capital cost is the installed cost to obtain a kilowatt-hour of energy per year. That is, the cost to procure, install and make ready generating capacity that will generate a kilowatt-hour per year. This measure, denominated in cents per kilowatt-hour per year (CkWh/Yr), is simply the installed capital cost divided by the annual energy production:²

$$C_{kWh/Yr} \equiv \frac{\text{Installed Capital Cost}}{\text{Energy Production per Year}} \quad (\text{Cents - Yr / kWh}) \quad (1)$$

Thus the specific capital cost CkWh/Yr includes the installed capital cost, the strength of the wind resource and the matching of the wind turbine power curve to the wind speed distribution. To estimate representative values of CkWh/Yr, we need to combine the assumed value of installed capital cost (\$1,000/kW) with the annual energy production. To do this, we utilize the energy production

corresponding to a capacity factor of 28 percent. The corresponding annual energy production value for a hypothetical 500 kW wind turbine is 1.226 million kWh/ Yr.³

Using this value of annual energy production and the installed capital cost value of \$1,000/kW, we calculate the corresponding value of the specific capital cost CkWh/Yr to be 41 cents/ (kWh/Yr).

This second cost measure, the specific capital cost, still is not all-inclusive. It does not include the costs of operation and maintenance over the lifetime of the facility, the costs of infrequent major overhauls or the cost of capital.

Life-cycle cost of energy

A windfarm's specific capital cost is the installed cost to obtain a kilowatt-hour of energy per year. Overview

The third and most comprehensive measure of wind energy cost is the life-cycle cost of energy (CoE). This measure incorporates all elements of cost:

1. Installed capital cost
2. Cost of capital
3. Costs of operations and maintenance (O&M) over the life of the installation
4. Cost of major overhauls and subsystem replacement.

This measure also includes the characteristics of both the wind resource and the wind turbine. The method used to estimate the CoE is a simplified version of the required revenue accounting methodology employed by some utilities⁴ to account for the stream of annually-recurring costs, costs that occur less frequently, economic assumptions such as interest and inflation rates, and a return on the financial assets employed. This sequence of estimated actual costs is projected over the 20- to 30-year lifetime of the installation. These costs are then levelized to obtain a single cost number that is equivalent to the multi-year sequence of estimated actual costs.

The multitude of cost elements may be combined into four categories. These are the installed capital costs, economic and cost of money assumptions, annually-recurring costs, and the costs of major overhauls and replacements that occur every five to 15 years. By taking into account the time value of money through net present value calculations, the cost elements are summed and then divided by the annual energy production to form the levelized CoE, with units of cents/kWh:

$$CoE = \frac{(ICC * FCR) + (O \& M) + (LAC)}{Energy\ Production\ per\ Year} \quad (Cents/kWh) \quad (2)$$

where **ICC = Installed Capital Cost (Cents)**
FCR = Annual Fixed Charge Rate (Percent/100)
O & M = Annual Operating & Maintenance Costs (Cents)
LAC = Levelized Replacement Cost (Cents)

Capital cost component

The capital cost component of the CoE is determined by spreading the installed capital cost over the selected lifetime of the installation. This is done on a straight-line basis using the Fixed Charge Rate (FCR). The FCR is the percentage of the installed capital cost allocated to each year of operation and

includes the costs of debt service. The capital cost component is analogous to a fixed-rate mortgage payment on a home, that is, a fixed amount per payment period over the lifetime of the debt.

The lifetime may be the projected physical lifetime of the installation or the accounting lifetime. The expected physical lifetime ranges from 20 to 30 years, while the lifetime used for accounting purposes may be less.

Note in equation 2 that the installed capital cost (ICC) divided by the annual energy production is the specific capital cost. With a FCR of 7.5 percent/year and a specific capital cost of 41 cents/(kWh/Yr), the capital cost component of the CoE would be 3.08 cents/kWh.

Operations and maintenance costs

The costs of operations and maintenance (O&M) include all normally-recurring costs associated with routine operation of the installed facility. The O&M costs do not include extraordinary or infrequently-incurred costs, such as major overhauls of the wind turbines and other systems. These costs are included in the LRC cost component.

The majority of the O&M costs are associated with maintenance. Maintenance costs generally are grouped into three categories:

1. The costs of unscheduled but statistically-predictable, routine maintenance visits to cure wind turbine malfunctions
2. The costs of scheduled preventive maintenance for the wind turbines and the power collection system
3. The costs of scheduled major overhauls and subsystem replacements of the wind turbine.

The first two of these occur during the course of a year and are included in the O&M cost component. The third occurs at intervals of five, 10 or 15 years, involves a financial accrual over the intervening years and thus is included in the LRC cost component (discussed below in the section on levelized replacement costs).

Life-cycle cost of wind energy incorporates all cost elements. The maintenance costs for modern windfarm turbines are 1 cent/kWh or less. The major component of the total maintenance cost is the unscheduled maintenance, followed as a distant second by the preventive maintenance and a still more distant third by the cost of the major overhaul and replacements. Assuming 0.9 cent/kWh, the total cost of maintenance thus might be apportioned as follows:

Unscheduled maintenance visits	75%	0.68 cents/kWh
Preventive maintenance visits	20%	0.18 cents/kWh
Major overhaul	5%	0.04 cents/kWh
Total cost of maintenance	100%	0.90 cents/kWh

These maintenance cost elements are discussed in more detail below.

Unscheduled maintenance. Wind turbines designed for use in windfarm arrays will have a small number of malfunctions each year. Typically these malfunctions are addressed by a two-person maintenance crew using a small truck equipped with tools, spares and diagnostic equipment. Often the repair is effected quickly, typically in one to four hours.

While such malfunctions are not predictable for a given wind turbine, their numbers are predictable over the course of a year. Usually, the wind turbine manufacturer, through a combination of operating experience and analysis, is able to provide estimates for each major subsystem of the wind turbine. In addition, the mean time to repair also can be estimated. These values, combined with the maintenance strategy (which leads to the mean-time-to-address the malfunction), enable the cost of unscheduled maintenance to be projected.

Preventive maintenance. Preventive maintenance visits, typically once per year for each wind turbine, can be scheduled. If the wind has a seasonal profile, then the preventive maintenance visits may be planned for the low-wind part of the year. Depending on the details of the design, the preventive maintenance visit typically may take a two-person crew about two hours per wind turbine. This minimizes lost energy production. Substation and power collection system maintenance may have more of an impact on energy production since all or part of the windfarm power delivery system is affected.

Major overhaul. As noted above, this maintenance cost element occurs only every five, 10 or 15 years, involves a financial accrual over the intervening years and thus is included in the LRC term of equation 5. This maintenance cost element is discussed below.

Modern windfarm turbine maintenance costs are 1 cent/kWh or less. Other operating cost elements

In addition to the costs of the operations and maintenance staff, replacement parts and other maintenance items, the O&M cost element typically includes other routine, annually-recurring operating costs:

1. Property and other taxes
2. Land-use payments
3. Insurance
4. Transmission access and wheeling fees
5. Management fees and general and administrative costs

The values of these operating cost elements vary depending on the situation. The local property tax structure, the land-use agreement, insurance rates and remaining fees vary from locale to locale and from one windfarm installation to another. Most are the result of specifically-negotiated arrangements. However, for the purposes of this paper, the range of variability is not as important as the typical values. Compared with the maintenance costs, these operating cost elements typically are small and in total contribute less than a half cent to the overall CoE. This is illustrated by the values presented in table 1.

Table 1 Estimated Values of Other Operating Cost Elements		
Operating Cost Element	Value (cents/kWh)	Basis for Estimate a
Property taxes	0.10	Assumed tax rate of 1% of depreciated facility value with a 20% floor, averaged over facility life
Land use	0.10	Assumed 2% of gross revenue @ 5

		cents/ kWh selling price
Insurance	0.003	Assumed insurance premium of 6.57 cents/ \$1,000 of valuation
Transmission/Wheeling	0.02	Single, quoted value
Substation maintenance	0.02	Assumed annual maintenance cost of 1.5% of substation cost @ \$30/kW
Management Fee/G&A	0.15	Assumed value
Total	0.39	Total of operating cost elements

a. All estimates proceed from the stated assumptions, and the hypothetical wind turbine and wind resource characterized by the values:

Power rating	500 kW
Installed capital cost	\$1,000/kW
Capacity factor	28%
Energy production	1.226 million kWh/Yr

Levelized replacement costs (major overhaul)

Depending on the details of the design, the major overhaul of the wind turbine occurs every five, 10, or 15 years. The major overhaul addresses the gears, bearings, seals and other moving parts. Usually the nacelle and the enclosed tower top machinery are removed from the tower and transported to a nearby depot maintenance facility. Often the removed nacelle and equipment are replaced immediately with a rebuilt assembly.

Short of a major overhaul, there may be subsystems that require infrequent replacement, that can be replaced with the nacelle still mounted atop the tower. Replacement of the wind turbine blades is an example of this category of infrequent subsystem replacement.

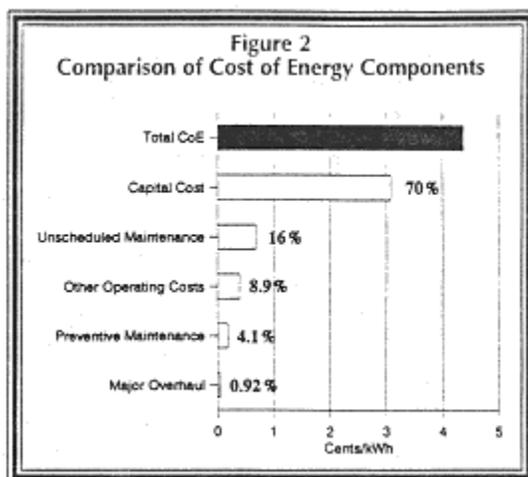
Because these costs are incurred at intervals of several years and not routinely during each year, correct accounting for their costs requires an annual accrual of funds. The objective of this accrual is to have the funds available when the need for overhaul or replacement occurs. The accrual involves a net present value calculation to level or apportion the overhaul and replacement costs to an annualized basis consistent with the other cost elements.

This element of maintenance cost was estimated above as 0.04 cents/kWh.

Total cost of energy

The cost of energy associated with wind turbines designed for windfarms has been resolved into the components of capital cost (via the Fixed Charge Rate), operations and maintenance costs, and the levelized costs of overhaul and major subsystem replacement. The estimated values are portrayed in figure 2 and summarized in table 2.

The relative magnitudes of these estimated values provide insight into where the overall economics of these systems may be impacted. From figure 2 and table 2, we see that the leading component of CoE is the capital cost, followed next by the costs of unscheduled maintenance. Together,



these two leading components represent 86 percent of the total CoE for this illustrative example. These values underscore the importance of reducing capital cost and of increasing reliability. These often contradictory goals represent one of the leading economic tradeoff issues faced by wind turbine designers.

Table 2 Comparison of Estimated Cost of Energy (CoE) Components			
CoE Component	Value (cents/kWh)	Basis for Estimate a	Percent of Total CoE
Capital cost (ICC*FCR)	3.08	Used FCR = 7.5%/year and Specific Capital Cost = 41 cents/(kWh/yr)	70%
Unscheduled maintenance	0.68	75% of 0.9 cents/kWh total maintenance cost	16%
Preventive maintenance	0.18	20% of 0.9 cents/kWh total maintenance cost	4.1%
Major overhaul (LRC)	0.04	5% of 0.9 cents/kWh total maintenance cost	0.92%
Other operating cost elements	0.39	Estimates from table 1	8.9%
Total CoE	4.37	Total of CoE components	100%
a. All estimates proceed from assumptions above and the notes for table 1.			

Summary

The three measures most used to describe the costs of wind energy systems have been defined and described. The cost measures have been illustrated with values appropriate to the wind energy application currently exhibiting the most attractive economics, namely, large-scale, grid-connected windfarms. The three measures are:

Most other operating costs are the result of negotiated arrangements.

1. The installed capital cost (ICC) of a complete, turn-key wind system, ready to generate and deliver electricity (units of \$/kW).
2. The specific capital cost, the installed cost to provide a unit of energy per year (units of cents/(kWh/Yr)).
3. The life-cycle cost of energy (CoE) (units of cents/kWh).

These cost elements are increasingly comprehensive. The installed capital cost includes only the equipment, facilities and infrastructure, designed, installed and ready to operate. It says nothing about the strength of the wind resource or the matching of the wind turbine power curve to the wind resource.

The strength of the wind resource is described quantitatively by the wind speed distribution, the number of hours per year that the wind speed lies within a given wind speed interval. The wind turbine power curve is the quantitative relationship between the electrical power output and the incident wind speed. The annual energy production is the integrated product of these two quantitative descriptions.

The second measure, the specific capital cost, incorporates the installed capital cost with the strength of the wind resource and its correlation with the wind turbine power curve. This measure is the installed capital cost normalized by the annual energy production. It thus serves as a measure of both the capital cost and the efficiency of conversion of wind to electrical energy.

The third measure, the levelized CoE, is the most comprehensive. This measure incorporates the installed capital cost, the cost of capital, the annual costs of routine operations and maintenance over the life of the installation, and the costs of infrequent major equipment overhauls and subsystem replacements. The sum of these costs, taking into account that some are spread over the 20- to 30-year life of the system, are then normalized by the annual energy production to arrive at the CoE.

These measures of wind energy system cost, together with illustrative values, are summarized in table 3.

Table 3 Summary of Cost Measures for Wind Energy Systems		
Cost Measure	Illustrative Value	Comments
Installed capital cost (ICC)	\$1,000/kW	Value appropriate for a large-scale, grid-connected windfarm
Specific capital cost (cost for capability to provide a unit of energy/year)	41 cents/(kWh/Yr)	Incorporates capital cost, wind resource and wind turbine characteristics
Life-cycle cost of energy	4.37 cents/kWh	Incorporates capital cost, cost of capital, wind resource and wind turbine characteristics, O&M costs, and costs of major overhauls

As summarized in the illustrative values of table 2, the leading component of the life-cycle cost of energy is the capital cost, followed next by the costs of unscheduled maintenance. For the illustrative values used, the capital cost represents 70 percent of the CoE. Together, the two leading components comprise 86 percent of the total CoE.

These values are illustrative of a windfarm installation with a total rated capacity of 50 MW. It was assumed further that the wind resource together with the wind turbine power curve was such that an annual-average capacity factor of 28 percent was achieved. For a 500 kW machine, this corresponds to an energy production of 1.226 million kWh/year.

A number of factors influence the cost of a windfarm. The actual cost for a given installation depends on the size of the installation, the difficulty of construction, the sophistication of the equipment and supporting infrastructure, and the cost of capital. Finally, costs of wind energy systems continue to decrease, and reliability to improve.

Notes

1. *Wind Performance Characteristics*.

2. The value used should be the net energy production, that is, with power collection and other losses removed. This is the actual energy delivered to the utility interconnection point.

3. The capacity factor is the ratio of two energy values. The numerator is the actual energy production for the specified period, here taken to be a year. The denominator is the hypothetical energy that would be produced if the system were able to operate at its full-rated capacity for the 8,760 hours in a year. A typical range of capacity factor values for windfarms is 24 percent to 30 percent.

The capacity factor is an alternate way to describe the energy production of a wind turbine or a windfarm. Thus, for example, a 500 kW wind turbine that produced 1.226 million kWh/yr would have a 28 percent capacity factor.

4. One widely recognized version is the Technology Assessment Guide method developed by the Electric Power Research Institute -- the so-called EPRI TAGTM methodology.

For further information

Further information about the characteristics of wind energy systems may be obtained from published articles and reports, laboratories maintained by the U.S. Department of Energy, the American Wind Energy Association and from wind turbine manufacturers and developers. Organization addresses and reference sources are listed below.

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Wind/Hydro/Ocean Division
Mail Stop EE-121
1000 Independence Avenue
Washington, DC 20585

References

Wind Energy Technology: Generating Power from the Wind (WET), published bimonthly by the U.S. Department of Energy, Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831. The March-April 1995 issue bears the publication numbers DOE/ WET-95/2 (PB95-933102) and ISSN:0896-5102 CODEN:WETWET. The publications are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, telephone (703) 87-4650.

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The Integration of Renewable Energy Sources into Electric Power Distribution Systems, Vol. 2, Utility Case Assessments, by H.W. Zaininger, P.R. Ellis and J.C. Schaefer, Oak Ridge National Laboratory, June 1994.

The cost elements of large-scale, grid-connected windfarms are increasingly comprehensive.

National Wind Coordinating Committee

The content and form of the papers in this series have been reviewed and approved by the National Wind Coordinating Committee. Committee members include representatives from investor-owned utilities, public utilities, state legislatures, state utility commissions, state land commissions, consumer advocacy offices, state energy offices and environmental organizations. The purpose of the National Wind Coordinating Committee is to ensure the responsible use of wind power in the United States. The committee identifies issues that affect the use of wind power, established dialogue among key stakeholders and catalyzes appropriate activities.

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