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July 20, 2004 — June 30, 2008

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Global Energy Concepts, LLC
Seattle, Washington

Subcontract Report
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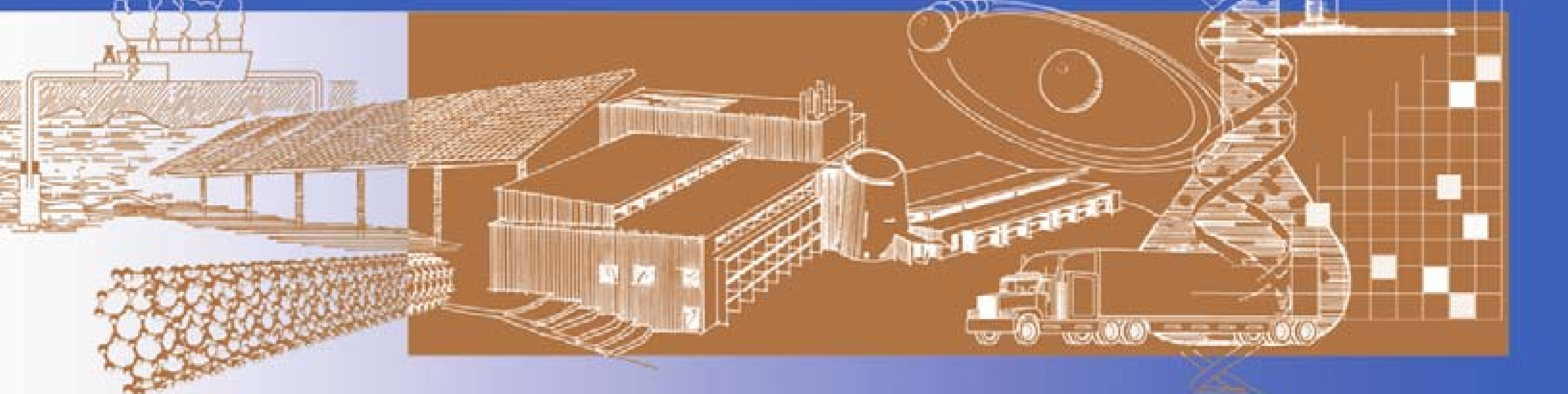

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1. Introduction

Global Energy Concepts, LLC (GEC) has developed an operations and maintenance (O&M) cost model for estimating O&M costs for commercial wind turbine generator (WTG) facilities. This model was developed under contract with the National Renewable Energy Laboratory (NREL). The overall objective of this model was to support the Low Wind Speed Turbine project goal of identifying ways to reduce the cost of energy for wind projects in low wind speed areas.

The model considers the typical costs associated with ongoing operations, including scheduled maintenance, unscheduled repairs, site management, and support personnel, of a facility that comprises any number of conventional wind turbines. Data from a variety of wind power projects that represent different turbine types, turbine ages, and geographic locations have been used to develop the assumptions. Since the operating record for turbines larger than 1 megawatt (MW) is limited to only 25% of the expected 20-year life, the model is necessarily speculative with respect to costs in the last 75% of project life. There are no series-production turbines in the 2 MW and larger range in North America, so estimates for such machines use extrapolated data. Nevertheless, the model is expected to be a useful tool for understanding the relative influences of the factors that drive O&M costs.

The model was created in an Excel workbook and will run on any PC with Microsoft Office. A brief user guide to the application is included in Appendix A. As delivered, the model includes a range of generic turbine sizes, with representative costs for parts and projected parts replacement rates, and default assumptions about staffing levels, labor rates, crane costs, etc. The user is only required to select the turbine rated power, pitch system type, rotor speed control type, and number of turbines for an "as-is" estimate of costs for a hypothetical project. However, the model is flexible. The user can change basic assumptions about the number of employees, labor rates, component costs, and crane rental rates.

The model is predictive rather than prescriptive. It projects costs, but does not directly identify methods for reducing the cost of energy. A key feature of the model is that it allows relative impact of the various O&M cost contributors to be evaluated on a common basis; this facility has not been available up to now. An example is the cost associated with maintaining an electric blade pitch system versus the cost for a more conventional hydraulic pitch system. Also, in the course of developing the assumptions for the model, GEC had the opportunity to observe different strategies for efficiently operating wind power facilities and to solicit recommendations and comments from experienced operators. These recommendations are included in Section 7 of this report.

The model produces estimates of O&M costs based on averages of past performance of equipment that is not always representative of current or future wind turbines. Significant changes have occurred in wind turbine technology over the past decade, in both scale and configuration. The megawatt-scale, pitch-regulated, variable-speed turbines that are common today have a relatively short track record. Most are still under warranty, so the reliability data for even this short time period are generally not available to the public. The component failures that do occur with newer machines often reflect a design that is not fully refined, and therefore may not be an accurate predictor of future reliability. The model does not reflect premature or serial failures, but rather uses failure rates that are appropriate for mature industrial equipment that has been field tested and proven.

Another variable that has an uncertain effect on wind turbine reliability is the condition of the site. The wind regime, as characterized by mean wind speed or turbulence intensity, certainly affects the turbine load spectrum, but the effect of increased loading on the reliability of components has not been considered in this study. Other site conditions, such as extreme temperatures and blown dust, will affect turbine operation and may prematurely degrade components such as fluid lines, wiring insulation, and electronics. The model does not reflect these effects.

Finally, not all turbine equipment is identical. The model assumes that all the turbines are equal in quality; that is, they are mature, proven designs, manufactured and installed with appropriate quality assurance measures, and supported by a competent service group. Still, variability between manufacturers, models, and even between individual turbines, is inevitable.

These factors (limited performance data of short duration, different site conditions, and variability of equipment quality) present challenges to developing a universally applicable estimating tool. To the extent possible, the model is based on quantifiable data, but some values are based on engineering judgment, as noted in the text. As discussed in Section 6, the model projections have been “benchmarked” with actual performance for selected projects. However, neither GEC nor NREL can guarantee that the results of the model will accurately reflect any individual project at any given time.

2. Scope

The O&M cost model that is presented here is applicable to conventional, three-bladed WTGs installed on tubular towers. This configuration is the *de facto* standard for current machines and represents the bulk of machines installed in North America in the last decade. In general these machines include full-span-pitch blades, a planetary/helical gearbox, and an induction generator. Although direct-drive machines represent a 15% world market share, there are few in North America at this time. GEC has no access to the performance data for those machines. However, the model can be configured to accommodate a direct drive if the cost and performance data are available to the user.

The generic turbines defined in the model include versions with either electric or hydraulic pitch systems and with either constant or variable rotor speed. No attempt has been made to estimate the costs associated with two- versus three-rotor blades, or with some of the recent innovative features such as permanent magnet generators. However, as stated previously, the model is flexible and has the capability to include any turbine configuration.

The scope of this study and of the model is also restricted as follows:

- Catastrophic events such as hurricanes, tornados, and lightning have not been considered. This is not to say that these events are not significant; lightning in particular has caused blade damage at numerous sites and will continue to be a risk as projects are installed in lightning-prone areas such as the Plains states.
- Retrofit work to remedy obvious design or manufacturing defects has not been included in the data that support the model. Components often fail during the first few years of a project, but we should not assume that these failures are representative of the reliability of that type of component. To do so would bias the failure distribution toward the anomalies rather than toward the norm. In some cases, the decision to exclude certain data is straightforward (e.g., where a "serial failure" has been declared). In other cases, the data point is an obvious outlier in the data set. These are discussed case by case as relevant.
- Repowering work (decommissioning equipment before the end of its useful life to install modern, usually higher powered equipment) has not been considered as part of the "failure" data. GEC has avoided data for projects where the motivation to maintain the equipment in optimal working condition has been damped by the prospect of decommissioning in the near future.
- Shipping and warehousing costs for parts are not included as line items. Given the variability and uncertainty of parts costs, and the number of options for warehousing spares, we may reasonably assume that shipping costs are included in the parts costs.
- Insurance costs were not included in the study; however, the model can be modified to include a placeholder.
- Balance-of-plant and substation maintenance costs were not specifically studied, but can be included with site maintenance costs at the user's discretion.

- Offshore turbines are specifically excluded from this study. The O&M costs for an offshore installation are uniquely driven by accessibility for service and repair and are not consistent with land-based costs. However, the model can easily be modified to include aspects that are peculiar to offshore projects, such as access intervals and repair times.
- Land-lease costs, interconnect fees, and royalties are not considered to be O&M costs.

3. Background

O&M costs have long been an uncertain but significant component of the cost of energy from wind power facilities. Much of the current understanding of O&M costs is based on limited knowledge of short-term operating expenses from wind farms, many of which use older turbines that are not representative of current designs, and where the wind farm is much smaller than those being installed in the United States today. This information is combined with estimates about the long-term reliability and replacement costs of major turbine components.

Because of the inexact nature of the input data, the O&M cost estimates that result from these analyses are imprecise; however, generally accepted approximations range from about $0.005 to $0.01/kilowatt-hour (kWh) for wind energy facilities in the United States. At low wind sites, where O&M per-turbine costs may remain fixed despite lower energy output, these costs may tend toward the high end of this range. Even higher costs may be incurred for smaller projects or where significant turbine repairs are necessary.

Considering the goal of the Low Wind Speed Turbine project to reduce the cost of energy to $0.03/kWh at Class 4 wind sites, minimization of O&M costs should be a significant concern. The model, and the data contained within this report, will provide some insight into the various factors that affect turbine O&M costs.

4. Source Data

Data for this project have come from a variety of sources, including manufacturer publications, published case studies, expenditures and service logs from operating wind farms, and conversations and interviews with project managers and technicians. The quality and quantity of the available data can best be described as spotty. In some cases general estimates of overall maintenance costs for specific projects for periods of one or two years were available; in other cases detailed information on actual expenditures for a variety of turbines (but only for a snapshot of their operating life) was provided. As expected, the data are not in a consistent format, and are broken down into a surprising variety of categories for parts, labor, and downtime.

Most importantly, there are no complete and consistent data for any project over the entire useful life of the turbines. Without exception, the older turbines (those reaching the end of their useful life) are smaller and simpler versions of the machines installed in the last five years. This distribution is consistent with the trend toward growth both in size and sophistication of wind turbines over the past 20 years.

Following is a summary of the available data sources for this study:

- Service logs from operating wind energy projects, which cover turbines that are smaller than 150 kW to nominally 2 MW, covering periods from one to six years.
- Parts consumption lists for operating projects, some of which include prices.
- Overall O&M summaries for current projects, including actual expenditures and projections.
- Spare parts price lists from manufacturers and receipts from actual projects.
- Interviews with operators and technicians about maintenance strategies, time to repair components, and time required for servicing.
- Manufacturer estimates of useful life and replacement rates for components.
- GEC's general experience and collective knowledge from evaluating and monitoring a variety of wind projects over the past 19 years.
- Published studies that are specific to wind project O&M costs and reliability of industrial equipment in general.

Since many of the data used in the study are from private sources and are considered proprietary, GEC has made a conscious effort to avoid reference to specific project sites or equipment manufacturers. Most of the data presented here have been averaged, and where possible normalized, to avoid distinguishing any particular entry. References in the public domain, however, are acknowledged where appropriate.

5. Approach

This cost model is loosely based on previous efforts by GEC to estimate O&M costs for specific projects that comprise specific turbines. The general approach, carried through to this project, is to identify the cost contributors and assemble them into a structure that extrapolates those costs over the operating life of the project. The model assumes a project life of 20 years. Certainly some projects have passed the 20-year mark, and some have been curtailed early by repowering with new equipment. However, 20 years is a common assumption for financing purposes and is representative of the design life for most commercial turbines.

Figure 1 shows the overall structure of the model. The database includes representative values for turbine and site service and repair parts, normalized to turbine size, height, and number. The required user inputs are in two broad categories: (1) characteristics related to the wind farm, such as number of turbines, assumed site capacity factor and expected sell price per kilowatt-hour; and (2) turbine characteristics, such as rated capacity, hub height, type of power conversion (fixed or variable speed) and pitch system.

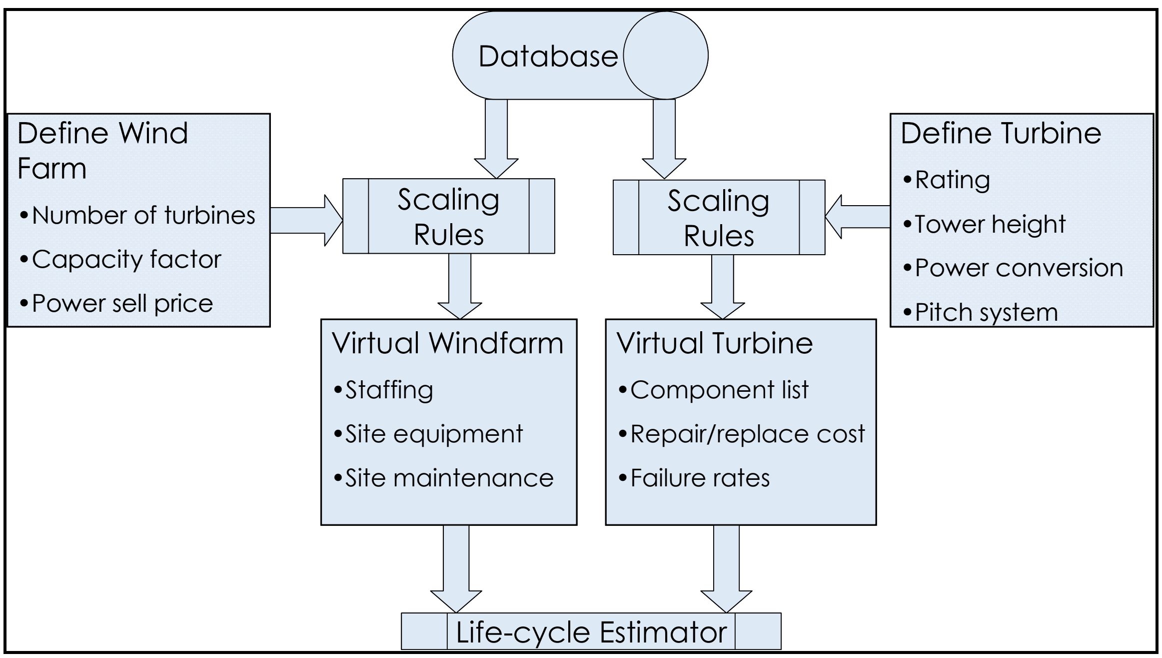


Figure 1. Database architecture

By default, the model creates a generic wind turbine as a proxy for commercial turbines. The reasons for this are partly practical: historical data for many of the turbines are limited and the cost data are generally proprietary. More importantly, a generic turbine allows extrapolation, on a common basis, from small to large sizes. This in turn allows the user to evaluate the relative benefits and disadvantages of using fewer large machines versus more small machines for a particular project.

The default turbine proposed in the model is based on the conventional three-bladed, pitch-regulated, upwind, tubular tower machine. The model offers selection sizes of 750 kW to 2.5 MW, with hub heights of 60 to 85 meters (m); this range brackets the current offerings in North America. Height is important in that it drives the cost of the crane used for repairs. Table 1 presents some common tower heights for the range of turbine ratings covered in the model. Other combinations of turbine rating and tower height are viable, and depend largely on the wind class at a specific site. In some cases higher towers may be proposed for the turbines rated 2.0 MW and higher. Unfortunately the number of cranes in North America that are capable of lifting the nacelle components to heights above 85 m is limited, and the cost for this type of lift is difficult to estimate.

Table 1. Typical Turbine Rating/Tower Combinations

Size	Tower (m)	Configurations	
750 kW	60	Hydraulic/electric pitch	Variable/constant speed
1.0 MW	65	Hydraulic/electric pitch	Variable/constant speed
1.5 MW	80	Hydraulic/electric pitch	Variable speed only
2.0 MW	80	Hydraulic/electric pitch	Variable speed only
2.5 MW	85	Hydraulic/electric pitch	Variable speed only

In addition to turbine sizes, options are included for turbine type, pitch actuation system, and rotor speed control. Since hydraulically and electrically actuated systems are currently used on commercial equipment, the model includes both versions for any size range. Even though variable-speed operation is currently limited to only one manufacturer, this option is available for all sizes under the assumption that variable speed will be offered by more manufacturers as the patents expire or licensing agreements are put in place.

Based on the input assumptions, the model uses scaling laws to populate the various cost contributors for the wind farm, based on the normalized data in the database. These costs are assigned to several categories (see Table 2). All these default assumptions are displayed, and the user can change any of them at will. This feature allows the user to refine the analysis to more accurately reflect conditions at a certain site, or even to add cost components that may be unique to a particular turbine. It also allows the user to evaluate the effect of different project configurations or operating strategies on O&M costs. For example, a 30-MW project that consists of 50, 600-kW turbines can be compared with one that consists of 10, 3-MW turbines.

Table 2. Cost Contributor Categories

Category	Description
Parts replacement	Costs for new and repaired parts, crane rental where required
Consumables	Turbine lubricants, filters and electricity consumed
Salaried labor	Site manager and office staff
Wage-based labor	Maintenance and service technicians
Site maintenance	Roads, fences, building, meteorological equipment
Equipment	Trucks, tools, office and shop supplies

Maintenance costs associated with options such as extreme weather operation, condition monitoring equipment, and service elevators are not included in the generic configurations. These can be added to the model as line items at the user's discretion.

5.1 Model Assumptions

The O&M costs have been segregated into the broad categories of *facility* and *turbine* costs to develop the assumptions used in the model. This breakdown is summarized as follows:

Facility Costs
- Operations and administration
- Site maintenance
- Equipment and supplies

Turbine Costs
- Labor
- Parts
- Consumables

In general, the facility costs will remain constant over the life of the project; the turbine costs will escalate as the equipment ages and components reach the end of their useful life. The final result is approximated in Figure 2.

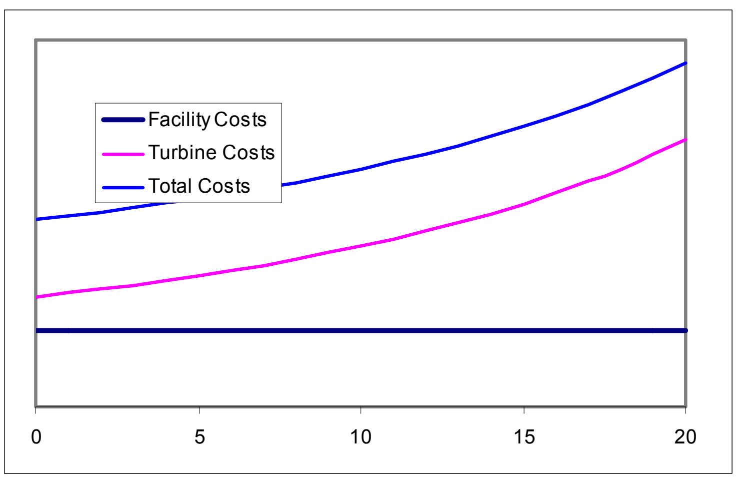


Figure 2. O&M Costs on a per-turbine basis

All costs for the entire period are presented in constant 2004 U.S. dollars (inflation in costs and labor rates is not considered). The next sections define the items in each category and discuss how the cost assumptions were reached.

5.2 Facility Costs

Facility costs are linked to the size of the facility and are assumed to remain constant over the life of the project. This implies that the infrastructure is maintained in good condition for the project's life and that no improvements or expansions are made. The model assumes that the project has a minimum of 18 turbines and a maximum of 100 turbines; this is on the high end of most installed projects. The following sections describe the assumptions that are used to create example wind power projects and the method used to derive these assumptions.

5.2.1 Operations and Administration

This category includes tasks associated with scheduling turbine crews, ordering and receiving parts for inventory, monitoring turbines status and performance, scheduling outside services for site maintenance, coordinating with the interconnect provider for outages and curtailments, and generating status and production reports. Since the most time-consuming activities are linked to the number of turbines, the model assumes that the manpower required for this activity depends only on the number of installed turbines, as opposed to the size of the turbine or the total capacity.

For a small facility with fewer than 20 WTGs, these tasks are commonly assumed by a working manager who also covers some of the turbine maintenance activities. As the number of turbines increases to more than 20, a dedicated manager is commonly assigned. For facilities with more than 40 turbines, the model assumes an administrative assistant will be required, and an additional support person is assumed for more than 60 turbines. These assumptions are summarized in Table 3.

Table 3. Manpower Levels by Number of Turbines

Project Size	<20 WTGs	21–40 WTGs	40–60 WTGs	60–100 WTGs
Manager	0.5	1	1	1
Support staff	–	–	1	2

5.2.2 Site Maintenance

Tasks that are not directly related to the turbine fall into this category. These include road maintenance, fence repair and brush clearing, maintenance building upkeep, meteorological equipment maintenance, and supervisory control and data acquisition (SCADA) system maintenance. Some activities may not be applicable to a specific site; others, such as snow removal, are applicable only to certain locations. The model assumes that these tasks are contracted to outside services, although depending on workload they may be assigned to turbine maintenance staff. Table 4 presents representative yearly expenditures.

Table 4. Representative Yearly Site Maintenance Expenditures

Project Size	<20 WTGs	21–40 WTGs	40–60 WTGs	60–80 WTGs	80–100 WTGs
Road grading	$3,000	$6,000	$9,000	$12,000	$15,000
Fences/clearing	$2,000	$4,000	$6,000	$8,000	$10,000
Building	$5,000	$10,000	$15,000	$20,000	$25,000
Meteorological	$5,000	$10,000	$15,000	$20,000	$25,000
SCADA	$1,000	$2,000	$3,000	$4,000	$5,000

5.2.3 Equipment and Supplies

Vehicles, tools, personal protection equipment, and supplies are collected in this category. General practice, for safety as well as practical reasons, is to dispatch two-person crews for any turbine maintenance work other than resetting faults. One vehicle and tool set are required per crew. Basic maintenance tools, special tools such as fixtures and rigging for removing large components, or remote terminals for communicating with the turbine controller for troubleshooting purposes, are provided with the initial turbine supply; replacements are included annually. Miscellaneous supplies are estimated for offices (paper, copier, utilities) and shops (fuel, personal protective equipment, rags, cleaners). Table 5 presents representative yearly expenditures.

Table 5. Representative Yearly Expenditures for Equipment and Supplies

Project Size	<20 WTGs	21–40 WTGs	40–60 WTGs	60–80 WTGs	80–100 WTGs
Vehicles	$12,000/crew	$12,000/crew	$12,000/crew	$12,000/crew	$12,000/crew
Tools	$8000/crew	$8000/crew	$8000/crew	$8000/crew	$8000/crew
Shop supplies	$2500/crew	$2500/crew	$2500/crew	$2500/crew	$2500/crew
Office supplies	$7000	$9000	$11000	$13000	$15000

5.3 Turbine Costs

Turbine costs are linked to size and configuration, and generally escalate over time as the machines age and parts wear out. As discussed in the following sections, labor costs and replacement parts costs are linked to turbine size and age; consumables are linked only to turbine size.

5.3.1 Labor

This category includes all staff who are dedicated to routine turbine maintenance, which includes regular turbine servicing, resets, troubleshooting, and minor repairs. Labor for major repairs, including any tasks that require a crane or more than a one hour of work for two technicians, is additionally included in the parts replacement cost.

A survey of a variety of sites indicates that the number of turbines that one technician can cover depends only slightly on the size of the machine. Figure 3 shows the number of turbines per technician for 10 representative sites, for turbines in the range of 500 to 2000 kW. The average number of turbines per technician is 16 and 12 for the smaller and larger machines, respectively, but the scatter within any group is very high. For these projects, which range from 20 to more than 100 MW installed capacity, there is no consistent trend between project size and number of technicians.

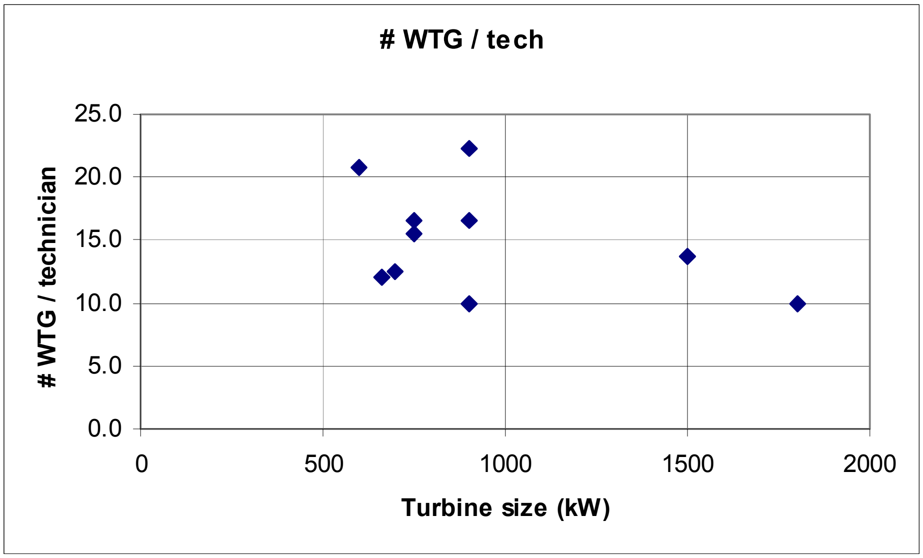


Figure 3. Number of turbines per technician

Several factors, including the tasks associated with regular servicing, the number of fault resets required, and the number and severity of repairs required, influence the time required to maintain a machine. Discussions with operators indicate that regular biannual service for modern turbines requires 20−40 hours; the wide range is associated with pitch-regulated machines. Time for repair and fault resets, excluding retrofit activities, is approximately equivalent to service hours. This ratio of service to repair hours is reasonably consistent with older projects.

As expected, the available data indicate that the total service hours per turbine, for similar size machines in the range of 500 to 1000 kW rated power, increases with turbine age and then levels off. Figure 4 shows the total annual service hours per turbine for four projects with similar size machines. The newer machines are slightly larger than the older machines, which suggests that their labor costs may level out at a higher cost as they age.

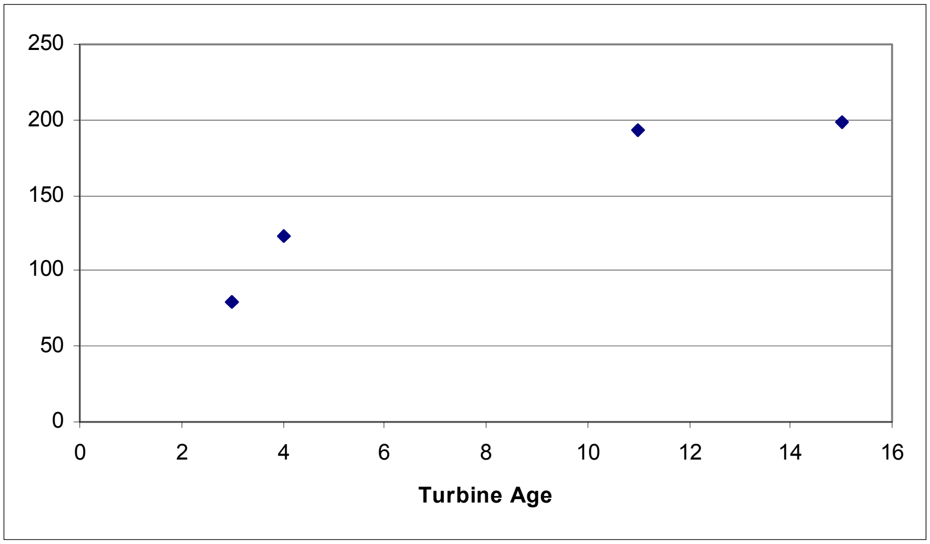


Figure 4. Annual service hours per turbine

Figure 4, shows the estimated hours required for turbine maintenance. Table 6 lists these assumptions for turbines. The labor hours assumed for maintaining higher rated turbines reflects the additional time required for turbine access and increased maintenance points. A reasonable number of hours that a full-time employee can effectively devote to maintenance work is 1800 per year; this accounts for 80 hours of vacation and sick leave, and 10% time devoted to administrative activities such as site meetings and safety training. The default crew sizes in the model are calculated by dividing the number of available hours per technician by the required hours per turbine. These estimates agree reasonably well with the data points for the first 10 years presented in Figure 3.

Table 6. Labor Hours per Turbine per Technician by Year

Period (Years)	1–5	6–10	11–15	16–20
750 kW to <1 MW	100	150	200	250
>1 MW to 2.5 MW	200	250	300	350

These relationships are used as the default values in the model to estimate turbine maintenance hours given the turbine size and the number of turbines assigned to the project. Even though technicians are routinely dispatched in two-person crews for practical and safety reasons, in some cases odd numbers are used in the analyses. This "extra" person can be considered to account for turnover, training, and relief time for other employees.

The model assumes the hourly rates for site staff that are shown in Table 7. These are representative of rates at operating projects. Technician rates will usually vary by skill level and experience, and often a crew will consist of a senior-level technician paired with a junior-level technician; these are average values for such a crew. Local rates can vary by 25% depending on the labor market in the area.

Table 7. Annual Labor Rates

	Base	Burdened @ 35%
Site manager	$30	$40.50
Technician	$18	$24.30
Administrative assistant	$33,000	

5.3.2 Parts

This category includes all replacement parts for the turbines, exclusive of consumables. The parts that are considered candidates for replacement, including mechanical, electrical, and hydraulic components, are those that wear or deteriorate during normal use. Mechanical parts that experience any form of friction, contact, or flexure (e.g., bearings, seals, gears, diaphragms, brake and yaw pads) are all candidates, although (as discussed in Section 5.3.4), the failure rate can vary dramatically depending on the design life and duty cycle. Fatigue of mechanical and structural components is explicitly omitted from the model, which assumes that the load-carrying components are designed with adequate design life for the imposed loads and duty cycle. For example, gearboxes are included in mechanical wear items, but the main shaft and bedplate are excluded. By the same reasoning, blades are assumed to structurally survive for the design life of the turbine, although the model assumes that minor blade repairs or refinishing to compensate for damage or wear will be required.

Hydraulic parts include pumps, valves and hoses, cylinders, and calipers. There are two distinct failure modes for these components, which have different failure distributions. In general, hoses will deteriorate over time regardless of use, and thus will have a calendar replacement schedule. The other components will wear based on use, and thus will have a replacement distribution based on operating hours. Electrical components such as contactors and circuit breakers that include contacts and moving parts are candidates for wear; main power cables are assumed to last for the life of the machine. Solid-state components such as control boards, power converter regulator boards, and soft-start trigger boards are included as they exhibit thermal deterioration over time. Motors and generators are included as the bearings wear mechanically and the windings fatigue thermally and mechanically with use.

The parts are segregated into the categories shown in Table 8. For each category, the major cost items are included and minor cost items are placed into a miscellaneous category.

Table 8. Parts Categories by System

Rotor	Blades, pitch bearings, pitch actuators
Drive train	Main bearing, seals, couplings
Gearbox and lubrication	Gearbox, lube pump, cooling system
Generator and cooling	Generator, power converter, cooling system
Brakes and hydraulics	Hydraulics, calipers, shoes
Yaw system	Calipers, wear pads
Control system	CPU, interface modules, sensors
Electrical and grid	Contactors, circuit breakers, relays, capacitors
Miscellaneous	Hardware, other small mechanical, hydraulic and electrical parts not identified specifically

As discussed earlier, an effort has been made to standardize the turbines to allow comparison on a common basis for different size machines. The components included in the generic configuration represent the current state of the art for modern turbines currently being supplied, although specifics will vary in the type of components included. These assumptions are described below for each component category.

- **Rotor:** The rotor is three-bladed with independent pitch for each blade. The pitch bearings are rolling-element type, and are periodically lubricated with grease. The pitch mechanism is one of two types: (1) hydraulic pitch systems, which include a pitch cylinder, proportional valve, crank arm mechanism, accumulator, and displacement transducer for each blade. The pump and position controller are common to all three mechanisms; and (2) electric pitch systems, which include a motor with position encoder, gear reducer, electronic drive, and backup battery bank for each blade. The position controller is common for all three mechanisms.
- **Control and Monitoring:** The control and monitoring system consists of a main controller in the turbine base, a remote controller in the nacelle, and another in the hub. The base unit contains a user interface and display. Control sensors include wind measurement instruments, rotor speed control, and power/grid monitoring transducers; sensors specific to monitoring component condition (e.g., PT100s for the generator) are included in that component category.
- **Drive Train:** The drive train consists of a main shaft supported by two main bearings, coupled to the gearbox with a hydraulic shrink coupling. A composite tube with flexure connections is used to couple the gearbox to the generator.
- **Electrical Power and Grid:** The turbine switchgear consists of a main breaker/disconnect, a line contactor for the generator power, and smaller contactors and circuit breakers for ancillary systems and power factor correction capacitors. A soft-starter is included for connecting to the grid for constant-speed machines.
- **Gearbox:** The gearbox is a combination planetary/helical unit with an integral lubrication system and fluid cooler system. The gearbox is suspended from the bedplate with elastomeric bushings.

- **Generator:** The generator is single-speed, induction type. The variable-speed machine includes a wound rotor and slip-rings. Cooling is provided by an integral forced-air system.
- **Brake:** The brake is a caliper-type located on the gearbox high-speed shaft. A dedicated hydraulic system provides pressure for the calipers. The brake is used only for parking, as the primary rotor brake is the blade pitch system.
- **Yaw System:** The yaw bearing is a sliding-bearing type with spring-applied calipers for stabilization. The surfaces are periodically lubricated with grease. The yaw drives are electric-motor driven with a multiple-reduction gearbox. The number and size of the yaw drives increase with turbine size.
- **Miscellaneous:** An overall category for miscellaneous parts that includes a value for parts not identified specifically elsewhere, such as hardware (brackets, pins, fasteners), small hydraulics (hoses, valves), and small electrics (contactors, lights, switches, connectors).

Parts costs for each of the five generic turbine sizes were estimated from machine cost data. In some cases these data have been drawn from manufacturers' price lists; in other cases they have come from actual receipts. The former data set is subject to an indeterminate markup; the latter is more limited in scope. All major wear parts are covered; minor parts are not included in the miscellaneous category. Those with a useful life approaching 20 years may be missing, but the impact of these omissions will be included in the margin of error for the major high-cost components.

Although small parts will likely be replaced in their entirety as they fail, larger components will likely be rebuilt. This is especially true of the high-priced components like the gearbox and generator, but applies as well to contactors, yaw drives, and power converters. Estimated replacement costs used in the model are based on rebuild cost where appropriate. The parts quantities and costs for the five generic turbines used in the model, along with the relations used to develop these costs, are included in Appendix B.

5.3.3 Consumables

Parts and supplies that are required for scheduled service, as opposed to repairs, are considered consumable. This category includes lubricants, filters, and cooling fluids. Parts such as brake pads and generator bushes, which are replaced indeterminately, are included in the parts category.

Annual turbine services generally include filter elements and greasing of the main bearing, yaw bearing and gear, pitch bearings, and generator bearings. Gear oil is mineral, as opposed to synthetic, and, according to common practice, should be replaced every three years. The model assumes an offline gear oil filter system and annual oil sampling. Hydraulic fluid will be replenished as required; this is generally a minor expenditure.

Table 9 lists these per-turbine consumable estimates for each generic turbine size in the model. Grease quantity is assumed to be scaled proportionally to turbine rated power. Consistent with the current gearbox design guidelines, gear oil quantity scales with turbine rated power at approximately 0.15 liters (L)/kW. Gear oil filter costs are assumed to increase linearly with gearbox oil quantity. Hydraulic filters are assumed to be constant with turbine size. Electricity for turbine ancillary equipment (heaters, lights, winch) is estimated at 2 kW/MW at $.05/kWh.

Table 9. Per-Turbine Annual Consumable Cost Estimates, $

Turbine Size	750 kW	1 MW	1.5 MW	2.0 MW	2.5 MW
Gear oil filter, ea	100	133	200	267	333
Hydraulic filter, ea	100	100	100	100	100
Offline filter, ea	100	100	100	100	100
Hydraulic oil, @$40/L	20	20	20	20	20
Gear oil, @ 3.70/L	140	187	279	371	464
Yaw gear grease @15/tube	60	80	120	160	200
Bearing grease @ $10/tube	45	60	90	120	150
Oil testing, ea	120	120	120	120	120
Electricity	657	876	1314	1752	2190

5.3.4 Failure Rates

The model estimates parts use by applying two types of failure rates to selected components, or categories of components. The first type of failure event is random, and is represented by a constant failure rate. The model assumes by default that 5% of the blades, main, yaw and pitch bearings, generators, and yaw drives will fail over the 20-year life of the project because of uncontrollable circumstances such as lightning strikes, manufacturer defects, operational errors, or servicing omissions and errors. Additionally, a miscellaneous category includes minor mechanical, hydraulic, and electrical parts such as fasteners, fittings, and switches, which are assumed to fail randomly throughout the project life.

The second type of failure event is wear out or deterioration, and is a two-parameter Weibull distribution. This distribution is commonly used in reliability studies as it allows for variation of the scale as well as the shape of the failure distribution. Weibull distributions are intended to describe failure rates for a given population of like components. Generally the most reliable data are obtained from exercising the components in actual or simulated conditions that are consistent over time. In an actual application, however, the parts that fail are replaced, so that the population eventually becomes a combination of components with varying periods of operation. At some point in time past the characteristic life, the instantaneous failure rate will oscillate about, and finally approach, a constant value.

The failure rates in the model are based on historical data from operating sites as well as published failure rates for similar components in similar applications. As discussed previously, the available data are sparse and incomplete. Although in some cases GEC has data for periods covering 20 years, these data are for different models and machine sizes throughout this time span. There are no reliable data for any one type of machine for a complete life cycle. Also, the meaning of *failure* is not always clear, as parts are sometimes replaced when they start to fail, and at other times when they have completely stopped functioning. For some part types (e.g., a control module), failure is definitive, but in other cases (e.g., a gearbox) a wide range of acceptable operating conditions may span significant periods of time.

Table 10 summarizes the failure rates, in terms of mean time between failures (MTBF), assumed in the model default turbines, along with representative failure rates from three other sources. MTBF, also referred to as mean life, is the period of time in which half a given population of like components is expected to fail. MTBF is a common metric used in reliability studies. It is related to the Weibull characteristic life by the following relation:

$$MeanLife = CharcteristicLife * (\ln 2)^{\left(1/\beta\right)}$$

Table 10. Estimates of Failure Rate Mean Life

Component	GEC model	Vachon [A]	Manufacturer Estimates	Weibull Database [B]
Blade failure	[C]	–	–	–
Blade refurbishment	[D]	–	–	–
Gearbox major failure	[C]	17	>20	14 -24
Gearbox helical section rebuild	24	–	–	–
Gearbox planet and helical rebuild	24	–	–	–
Generator major failure	[C]	14	>20	28
Generator bearing replacement	15	–	15	14
Yaw drive	[C]	15	10	14–24
Yaw sliding pads	9	10	>20	42
Pitch bearing	[C]	10	>20	14
Main bearing	[C]	–	>20	14
Pitch cylinder	9	10	5–10	14
Hydraulic valve	11	10	10	26
Accumulator	5	10	5	16
Hydraulic pump	11	–	–	–
Brake caliper	8	20	20	14
Lube pump	11	–	10	10
Cooling fans	14	–	>20	28
Main contactor	17	–	–	–
Main circuit breaker	25	–	–	–
Control board, main	12	–	–	
Sensor, static	12	–	10–15	33
Sensor, dynamic	10	–	10–15	7
Power electronics	12	–	–	23
Soft starter	25	–	–	–

A – Vachon, W.A. "Modeling the Reliability and Maintenance Costs of Wind Turbines Using Weibull Analysis." Windpower '96 Conference Proceedings.

B – Barringer Associates, Inc. *Weibull Database*. www.barringer1.com/wdbase.htm.

C – Assume 5% random failure rate for 20-year project life.

D – Assume 100% require refurbishment over 20-year project life.

The discrepancies in Table 10 for any one component can be partially explained by the uncertainty of the sources. The data presented by Vachon are limited to one particular era of wind turbines that had operated for 14 years at the time of the study, with missing data for a portion of the early years. Vachon also assumed a constant shape parameter β of 3.5, which represents a symmetrical distribution. This is not consistent with the shape parameters in the Weibull database, which are generally less than 2. The data set for the Weibull database includes a wide variety of component types and operating conditions, and is not necessarily representative of the purpose-designed components in a commercial wind turbine. Appendix C discusses the failure rate assumptions used in the model for selected components, along with GEC's rationale for selecting the Weibull parameters.

5.3.5 Time to Repair

The values used in the model for time to repair or replace a component are based on discussions with operators and technicians and estimates provided by several manufacturers. In some cases GEC did attempt to verify these estimates with service logs, but the lack of consistency in the recording and presentation of the logs allowed for only a rough check.

The model only includes time for repair of major components; that is, those that require rigging of some sort and a repair time of more than two hours. Repair time for all other components is assumed to be covered by the general service hours allocated in Section 5.3.1. The model assumes that where required, replacement parts are readily available and that no significant transport or wait time is required. This is consistent with most large facilities that have a stock of spares, including gearbox and generator, but this may not be a valid assumption for smaller facilities that use a central manufacturer's depot for parts. Table 11 lists the assumed repair times in man-hours. These include shop preparation time.

Table 11. Assumed Repair Time (Man-Hours)

Turbine size	750 kW	1 MW	1.5 MW	2.0 MW	2.5 MW
Blade[1]	30	30	40	40	50
Pitch cylinder	6	10	12	14	16
Pitch bearing	50	50	60	70	80
Pump and hydraulics	8	8	8	8	8
Pitch position transducer	4	4	4	4	4
Pitch motor	4	4	4	4	4
Pitch gear reducer	6	6	6	10	12
Pitch drive (electronic)	4	4	4	4	4
Main bearing	100	110	120	130	150
High-speed coupling	12	12	12	12	12
Gearbox remove and replace	70	80	90	100	120
Lube pump	4	4	4	4	4
Cooling fan/pump	4	4	4	4	4
Generator R&R	16	18	20	22	24
Generator bearing replacement[2]	10	10	10	10	10
Power electronics	8	8	8	8	8
Generator cooling fan	4	4	4	4	4
Generator contactor	4	4	4	4	4
Brake caliper	6	6	6	6	6
Accumulator	4	4	4	4	4
Hydraulic pump	4	4	4	4	4
Hydraulic valve	4	4	4	4	4
Yaw drive R&R	8	8	8	8	8
Yaw caliper	8	8	8	8	8
Yaw sliding pad	8	8	8	8	8
Main circuit breaker	4	4	4	4	4
Soft starter	8	8	8	8	8
Pitch gearbox R&R	6	10	12	14	16

[1] Assumes removal of one blade only
[2] In situ replacement

5.3.6 Cranes

The model assumes that the wind energy facility rents a crane for any major replacement, and that the replacements will occur on a per-unit basis. That is, the advantages of multiple replacements with one crane rental will not be realized (or required) for a site that follows the failure assumption proposed in the model.

Crane rental costs are driven by crane capacity and mobilization time. Discussions with crane rental companies confirm the conclusions from previous studies: the crane capacity required for removal and replacement (R&R) of the two large components (gearbox and generator) is driven by height, not weight. Two common crane types—conventional crawler cranes and truck-mounted cranes—are appropriate for wind turbine component replacements. Cost for the former is driven by mobilization, as the crane and boom are shipped in pieces and require 10 to 20 truckloads, depending on height. Hydraulic truck-mounted cranes use a telescopic boom and require only one to three additional loads for counterweights, and are significantly cheaper to mobilize, but generally cost more per hour. Conventional cranes are sometimes available in a truck-mounted version, but still require multiple loads for the lattice boom and jibs.

For both cranes types, the height and reach are maximized by adding boom extensions (fixed jib or luffing jib) to obtain the required reach over the nacelle structure. As height and reach increase, additional counterweight must be attached to the crane body. The lift capacity decreases with height and reach. Fortunately, the weights of major turbine components are relatively small compared to crane tonnage, so that in most cases a given crane can be maximized for height. Figure 5 and Figure 6 show representative weights for gearboxes and generators for current model wind turbines.

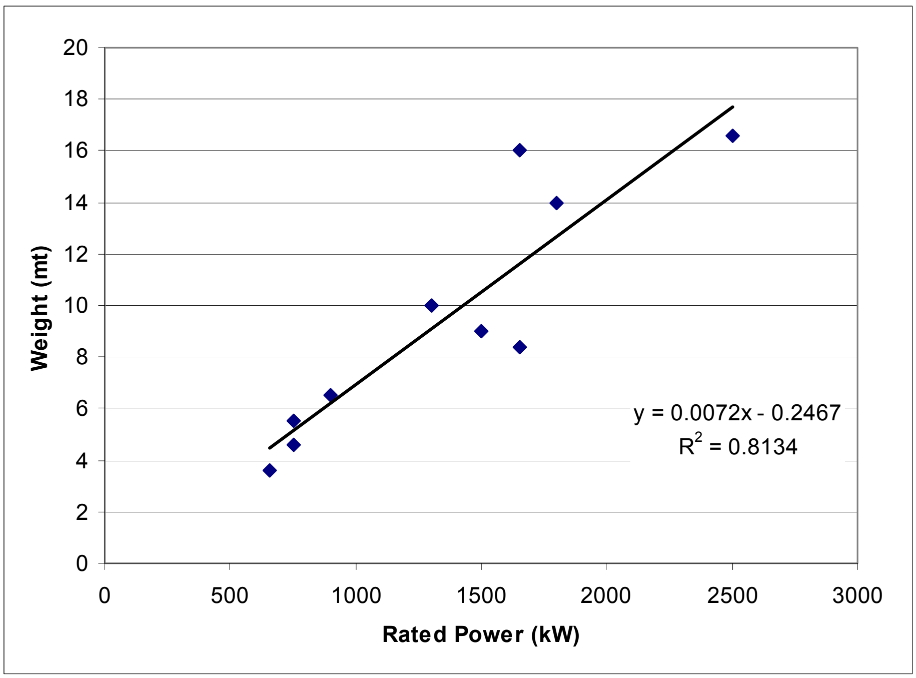


Figure 5. Representative gearbox weight

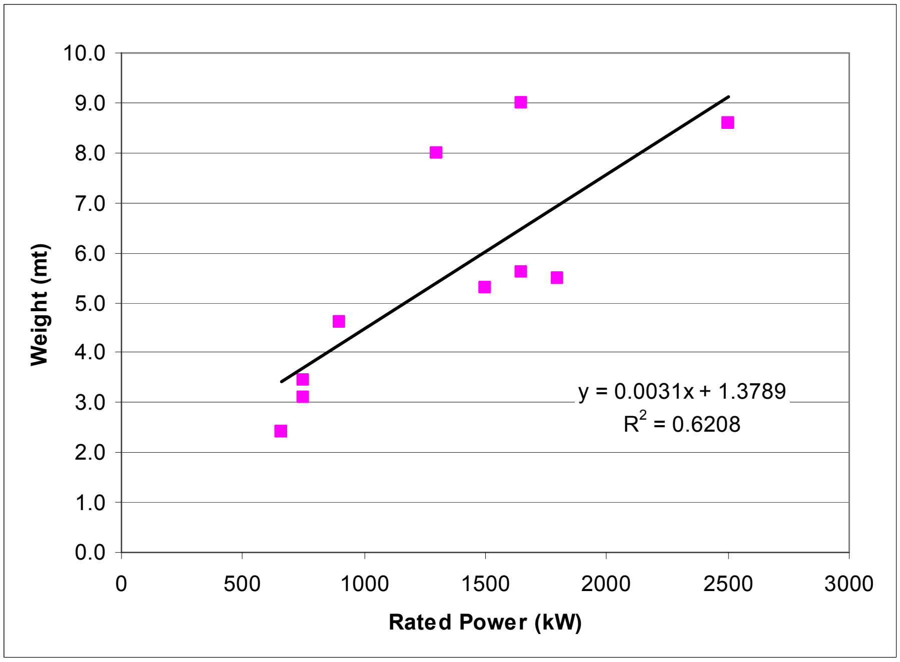


Figure 6. Representative generator weight

In general, the candidate cranes for wind turbine work are limited to discrete sizes, and not all of these are readily available near the turbine site. Figure 7 shows example costs for cranes used for R&R of a gearbox at projects in a variety of locations, along with estimates for similar work provided by crane leasing companies. The lower tonnage equipment is truck-mounted hydraulic equipment and the higher tonnage is conventional crawler type.

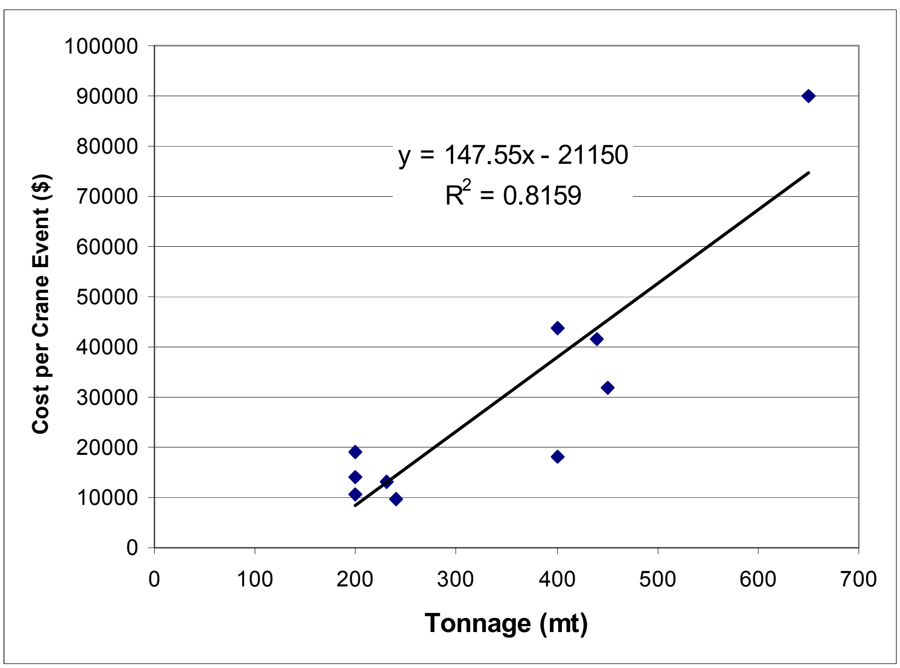


Figure 7. Crane costs by tonnage

Table 12 through Table 14 list appropriate cranes for the five generic turbine sizes proposed in the model, along with representative costs for one day of R&R work and in/out mobilization. These are the default values in the model. The associated costs, which are based on experience with operating projects, include a second assembly crane, fuel, insurance, operator, and rigger for a lattice-type crawler crane. Mobilization cost assumes one day of travel each way from the rental depot.

For the larger turbines, it is becoming more common to offer a nacelle-mounted crane for removal of the generator. This option is available on several large commercial machines, but there is little evidence the internal option is being purchased. Thus, the model currently assumes no internal crane to remove and replace the generator or other components for 2- and 2.5-MW models. Crane costs can be added or removed in the entry sheet, thus simulating an internal or external crane. An example of this is shown at the end of Section 6.

Table 12. Gearbox and Main Bearing R&R Crane Assumptions

Turbine size	750 kW	1.0 MW	1.5 MW	2.0 MW	2.5 MW
Tower height	60 m	65 m	70 m	80 m	85 m
Gearbox weight	5.5 mt	7 mt	10 mt	16 mt	18 mt
Crane size	200 ton	240 ton	400 ton	400 ton	650 ton
Crane type	Truck-mounted hydraulic	Truck-mounted hydraulic	Conventional crawler	Conventional crawler	Conventional crawler
R&R cost	$10,000	$25,000	$50,000	$70,000	$90,000

Table 13. Blade and Pitch Bearing R&R Crane Assumptions

Turbine size	750 kW	1.0 MW	1.5 MW	2.0 MW	2.5 MW
Tower height	60 m	65 m	70 m	80 m	85 m
Blade weight*	1.5 mt	2.9 mt	4.3 mt	6.5 mt	8.1 mt
Crane size	200 ton	240 ton	400 ton	400 ton	650 ton
Crane type	Truck-mounted hydraulic	Truck-mounted hydraulic	Conventional crawler	Conventional crawler	Conventional crawler
R&R Cost	$10,000	$25,000	$25,000	$70,000	$90,000

* Griffin, Dayton A. *WindPACT Turbine Design Scaling Studies Technical Area 1 – Composite Blades for 80- to 120-Meter Rotor, March 21, 2000 – March 15, 2001*. National Renewable Energy Laboratory. NREL/SR-500-29492, April 2001.

Table 14. Generator R&R Crane Assumptions

Turbine size	750 kW	1.0 MW	1.5 MW	2.0 MW	2.5 MW
Tower height	60 m	65 m	70 m	80 m	85 m
Generator weight	3.5 mt	4.6 mt	6 mt	7.5 mt	9 mt
Crane size	200 ton	200 ton	240 ton	400 ton	650 ton
Crane type	Truck-mounted hydraulic	Truck-mounted hydraulic	Truck-mounted hydraulic	Conventional crawler	Conventional crawler
R&R cost	$10,000	$25,000	$25,000	$0	$0

6. Results

The model provides results in a variety of forms, including cost tables for each major category on a project, per-turbine, and per-kilowatt-hour basis. Tables also list the cost assumptions for all turbine parts and the total number of parts used in the 20-year project life. Copies of complete results from each model run are included in Appendix D.

The results show total costs associated with scheduled maintenance, unscheduled maintenance, and levelized replacement costs (LRC). The last category is commonly used to estimate reserves that will be required for major component overhauls or replacements. The failure rate and cost estimates provided by the model could be used to inform the process for establishing the required monetary reserves to cover LRC. Also, the model does not account for lost revenue caused by turbine downtime for repair or service, as this is usually accounted for in the project availability assumptions.

Figure 8 presents graphical results of executing the model with the five generic turbine sizes. The chart shows estimated costs on a per turbine basis. The configuration for each size is consistent with most currently available commercial turbines. The project size in each case is 60 MW and the calculations assume a capacity factor of 35%.

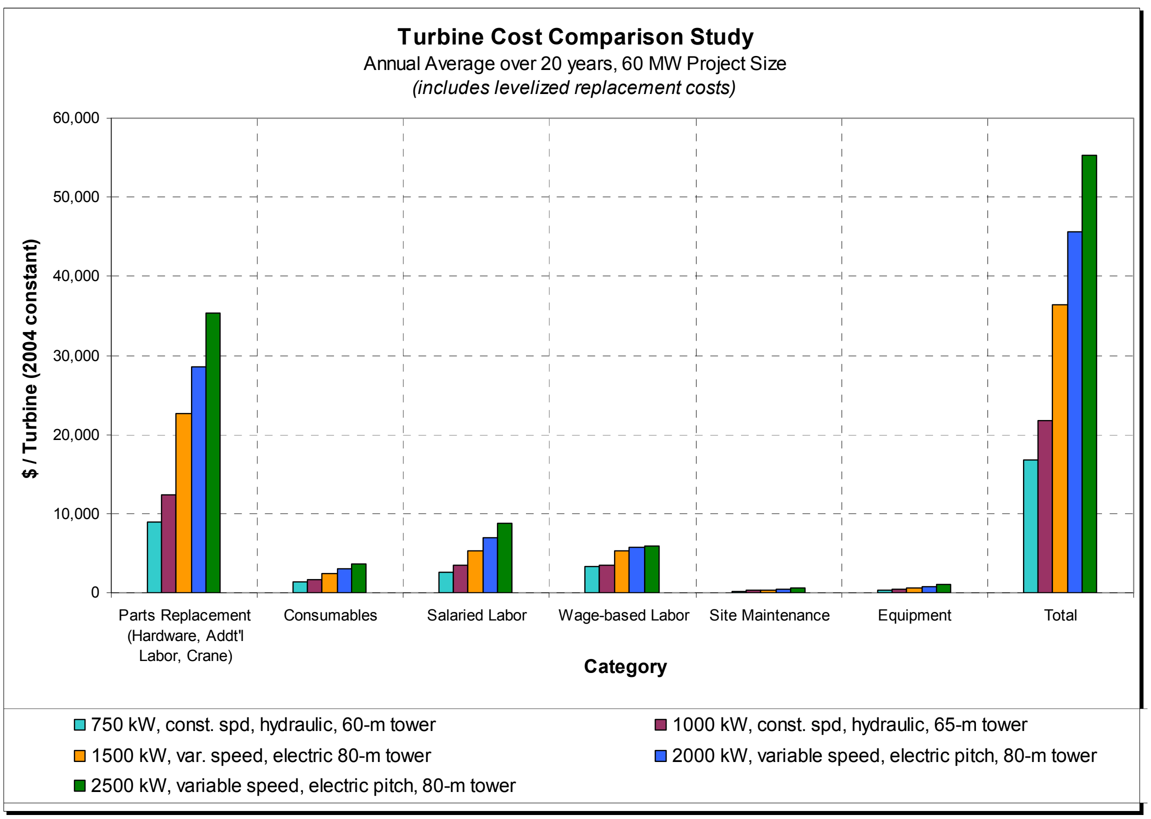
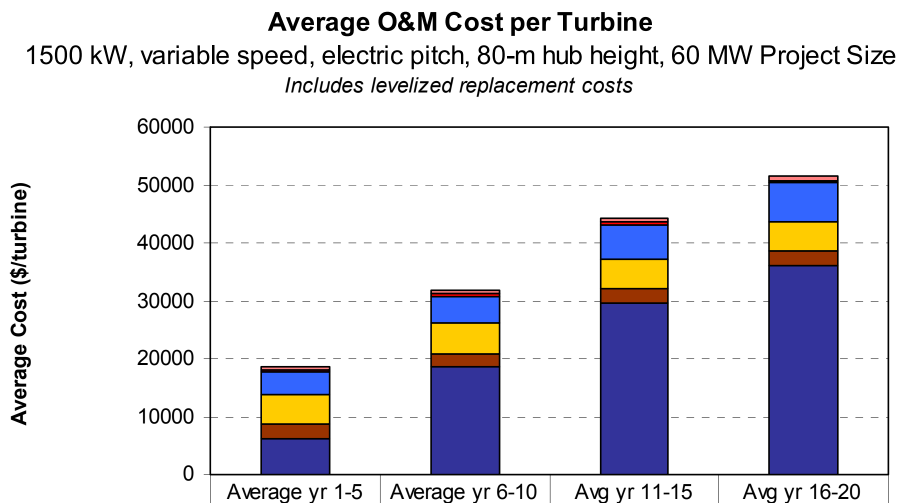


Figure 8. Cost per turbine ($), 20-year project life

The O&M cost estimates for the five turbine sizes demonstrate that the major contributor to overall O&M costs over the project life is parts replacement, followed by labor. Figure 9 shows that in the first 5 years, parts costs are estimated to be 30% of the total cost, and by the end of the project life, they exceed 65% of the total cost. Additionally, if the 20-year average of $37,000 per turbine were used to gauge warranty costs for contract negotiations, rather than the average for years 1−5 of $19,000, valuable reserve funds could easily be forfeited to the warranty service provider.



	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20
Equipment	600	600	600	600
Site Maintenance	353	353	353	353
Wage-based Labor	3791	4633	5897	6739
Salaried Labor	5231	5231	5231	5231
Consumables	2348	2348	2348	2348
Parts Replacement (Hardware, Addt'l Labor, Crane)	6333	18588	29695	36154

Period

Figure 9. O&M Costs per turbine, 5-year averages

Looking at the 1500 -W turbine size in the study, parts costs are dominated by the failure of large parts that require the use of a crane (see Figure 10 and Figure 11).

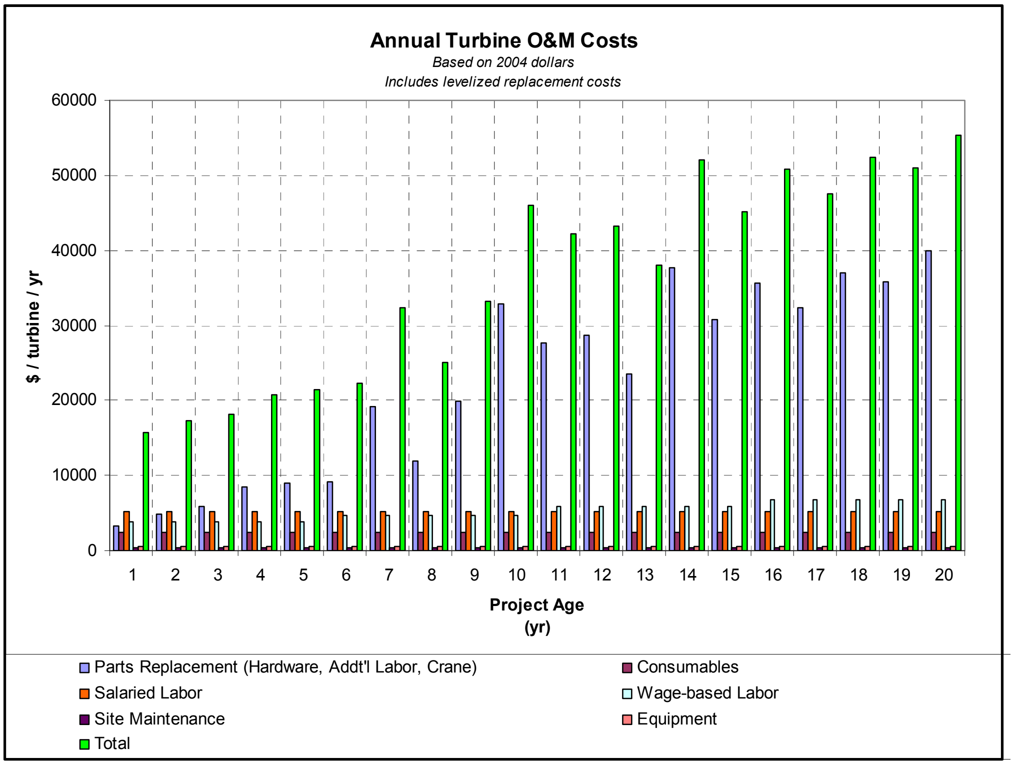


Figure 10. Annual turbine O&M costs

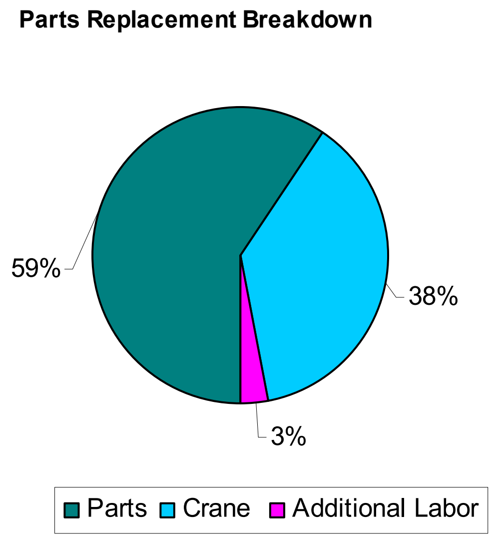


Figure 11. Crane costs

The bumpiness is an artifact of the high-cost infrequent events, and will be accentuated as the number of turbines in the project decreases. An indication of where the high costs are occurring can be found in Figure 12, which shows that the gearbox (including lubrication) and rotor systems are the largest cost drivers.

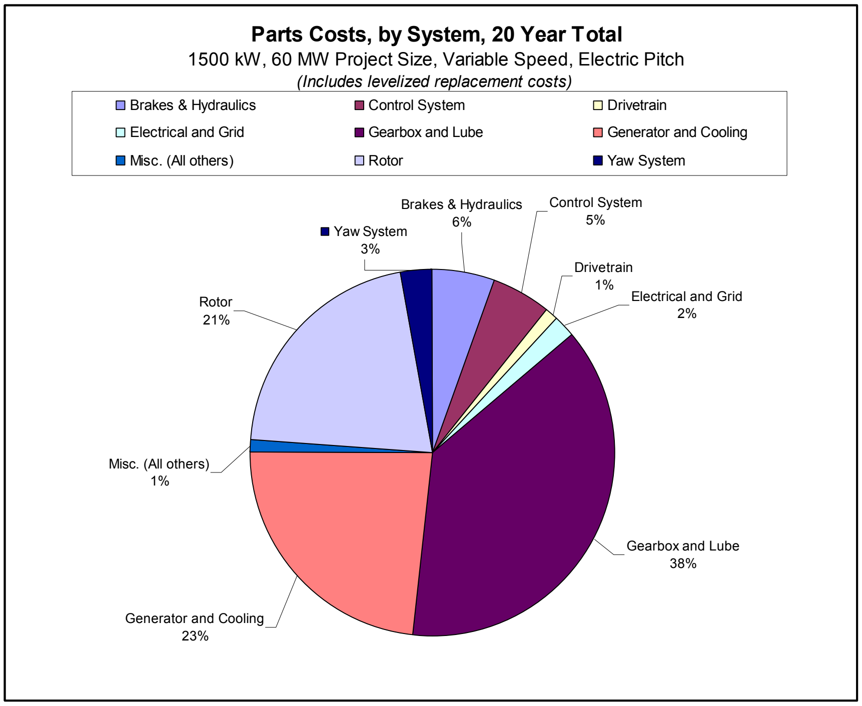


Figure 12. Parts costs over 20 years, by system

A closer examination shows the failure distribution for some major components in each system (see Figure 13). An increase in major failures is noticeable around year 7 when the first gearbox failures are assumed to occur, and later in year 10 when coincident gearbox and structural blade failures are projected.

Cumulative failures or replacements by year (major components)																								
System	Component	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	Parts in Project	Repair or Replacements in 20 yrs per Project	Total Failures over 20 yrs / initial qty parts in fleet (%)
Rotor	Blade--struct. repair	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	1	72	3	4%
	Blade--nonstruct. repair	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	72	72	100%
Drivetrain	Main bearing	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	24	1	4%
Gearbox and Lube	Gearbox--gear & brgs	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	24	1	4%
	Gearbox--brgs, all	0	0	0	0	0	0	1	0	1	1	2	2	1	3	2	3	2	3	3	2	24	15	63%
	Gearbox--high speed only	0	0	0	0	0	0	1	0	1	1	2	2	1	3	2	3	2	3	3	2	24	15	63%
Generator and Cooling	Generator--rot. & brgs	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	24	1	4%
	Generator--brgs only	0	0	0	0	1	1	2	2	3	4	4	6	5	6	7	6	7	7	6	5	48	43	90%
	Power electronics	0	1	1	1	2	1	2	2	3	3	3	2	4	3	3	3	3	3	3	3	24	26	108%
	Total	6	7	7	8	9	8	13	10	14	19	17	18	17	22	20	21	21	22	21	22			

Figure 13. Failure distribution over 20 years, major parts

Although the timing and frequency of these events will vary from site to site, their occurrence will have a major impact on site resources. Projects usually maintain budget reserves for just this contingency, and may rely on additional short-term labor resources.

A trend in O&M costs as turbine size increases can be demonstrated with two additional common metrics that are used to evaluate project and turbine performance. Higher rated turbines are projected to cost less per kilowatt irrespective of age. This effect is demonstrated in Figure 14, which shows three turbine sizes of identical architecture (variable speed, electric pitch, 80-m towers).

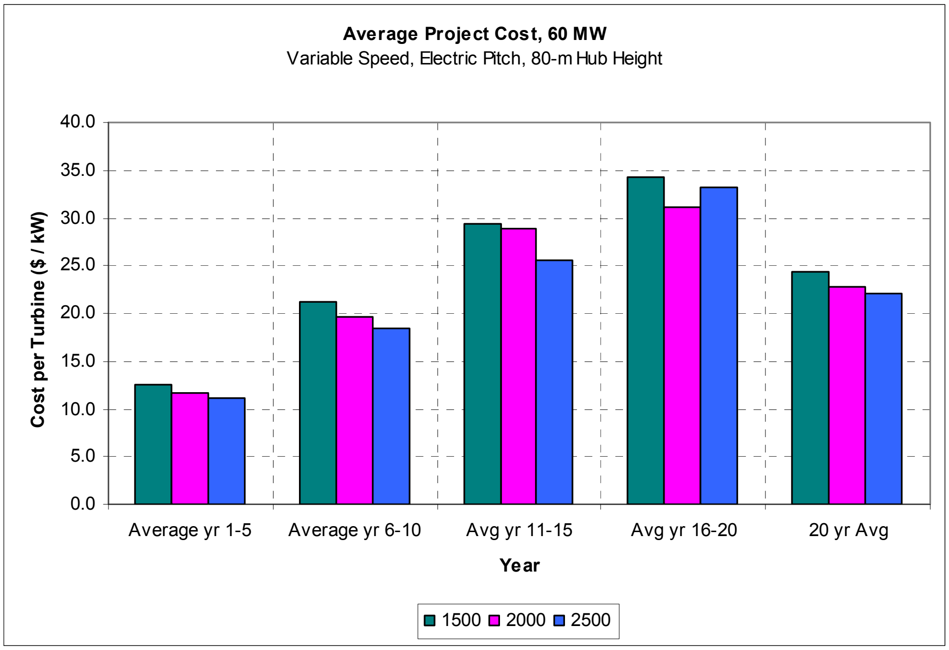


Figure 14. Average cost per kW, 60-MW project

Finally, Figure 15 shows the per kilowatt-hour change in cost. The trends for this metric parallel the trends shown above. This must be so, because a constant capacity factor of 35% has been used in all the models. Figure 16 is an annual look at the data in Figure 15. Along with Figure 17, it shows that the high O&M cost for 2500 kW turbines in years 16–20 was caused by a compounding of failures in year 16.

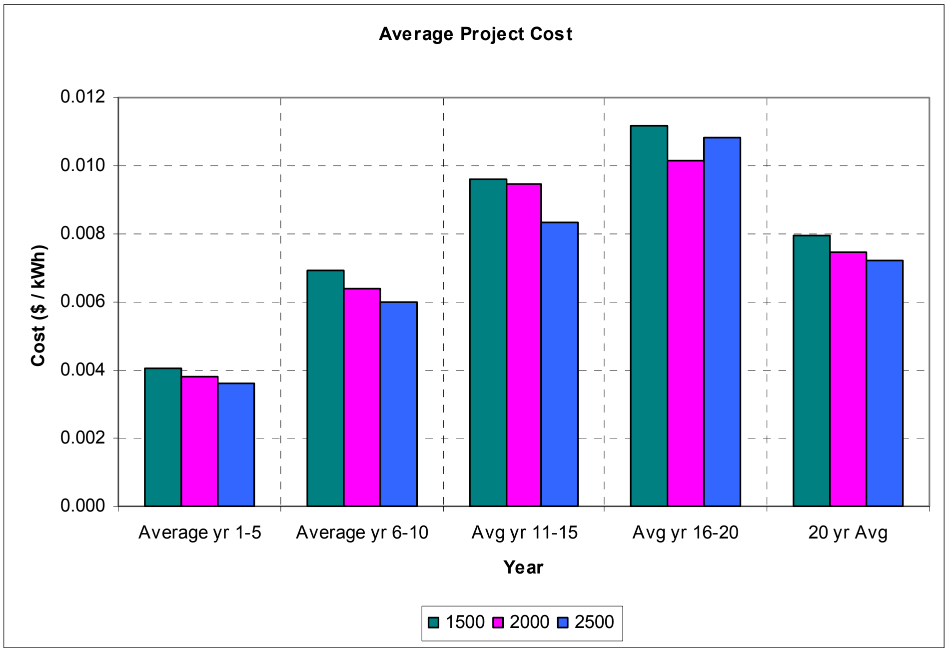


Figure 15. Average cost per kWh, 60-MW project

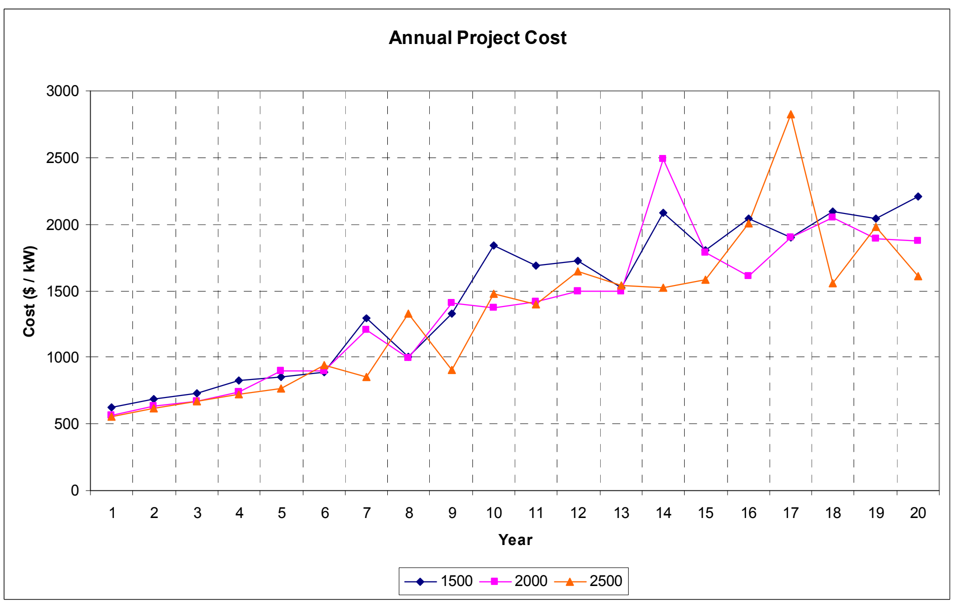


Figure 16. Annual project cost

Cumulative failures or replacements by year (major components)																								
System	Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Parts in Project	Repair or Replacements in 20 yrs per Project	Total Failures over 20 yrs / initial qty parts in fleet (%)
Rotor	Blade--struct. repair	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	72	3	4%
	Blade--nonstruct. repair	3	4	3	4	4	3	4	3	4	4	3	4	3	4	4	3	4	3	4	4	72	72	100%
Drivetrain	Main bearing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	24	1	4%
Gearbox and Lube	Gearbox--gear & brgs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	24	1	4%
	Gearbox--brgs, all	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	2	2	1	2	1	24	15	63%
	Gearbox--high speed only	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	2	2	1	2	1	24	15	63%
Generator and Cooling	Generator--rot. & brgs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	24	1	4%
	Generator--brgs only	0	0	0	0	0	1	1	2	1	3	2	3	4	3	4	4	4	4	3	4	48	43	90%
	Power electronics	0	0	1	1	1	1	1	1	1	2	1	2	1	2	2	2	2	1	2	2	24	26	108%
	Total	3	4	4	5	5	6	6	8	6	11	8	12	10	11	12	13	18	10	13	12			

Figure 17. Annual failures of 2.5 MW major components, 60-MW project size

A change in architecture such as hub height can affect the O&M costs, so the model is useful for making project development decisions in conjunction with other estimates of project performance, such as hub-height power production. Figure 18 shows the effect of increasing the tower size from 80 to 100 m.

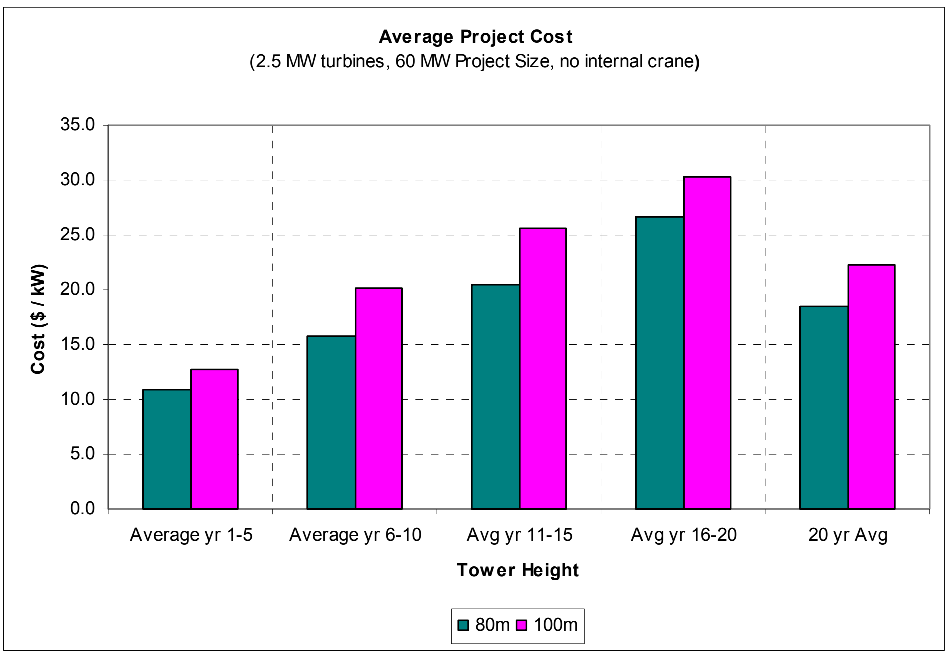
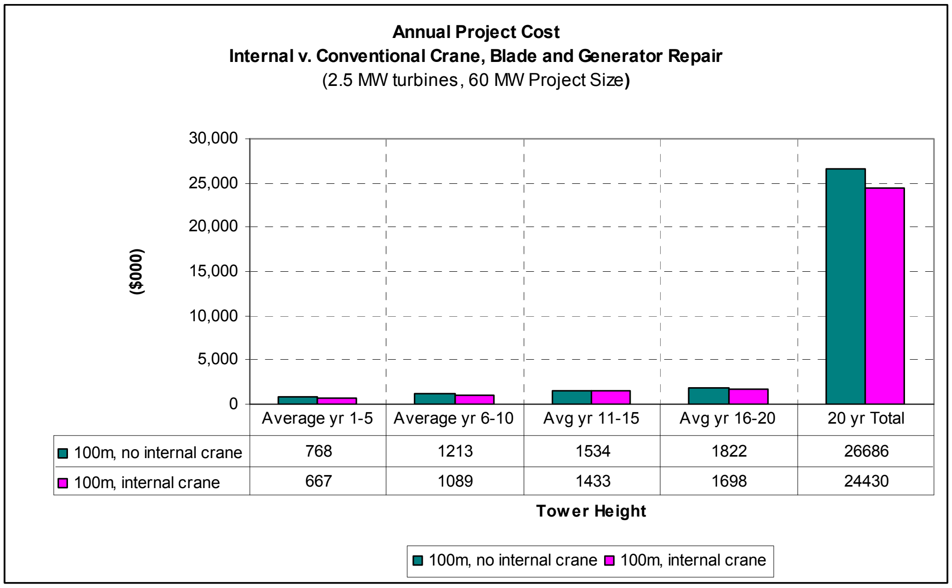


Figure 18. Estimated O&M costs for 2.5-MW Turbines on 80-m versus 100-m towers

Other studies, such as whether O&M cost savings can be achieved by using an internal crane, can be performed. In Figure 19, the comparison shows savings of more than $2 million if an internal crane can lift blades and generators. The developer may be able to decide whether to use the internal crane based on expected use and the additional cost of an internal crane.



	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Total
100m, no internal crane	768	1213	1534	1822	26686
100m, internal crane	667	1089	1433	1698	24430

Figure 19. Effect of internal crane on O&M costs

7. Reducing O&M Costs

Discussions with operators revealed several approaches to project operations that may reduce O&M costs. All these tactics are currently being implemented to some degree at most large wind projects, and, except for “Innovative Rigging and Tooling,” are common strategies for any industrial operation.

7.1 Assign Tasks to Outside Services

Owners typically contract outside service organizations to provide some or all of the O&M services, especially in the early years of a project. After several years, the owner may then decide to self-manage the project. Irrespective of who manages the project, specialty tasks that require specific training or equipment, such as road maintenance or transformer inspections, are usually hired out. Depending on the workload caused by repair activities, a project may contract an outside service to perform biannual turbine servicing. This is not necessarily a less expensive option per turbine, but it does allow the project to focus trained technicians on the difficult tasks and avoid hiring additional permanent staff.

7.2 Condition Monitoring

All modern wind turbines have some form of condition monitoring for critical components. Critical parameters such as bearing and lubricant over-temperature are usually integrated into the turbine control system. Regular testing of gear oil and thermographic testing of transformers are now required (or at least recommended) by manufacturers. Vibration and acoustic analysis for bearings is increasingly being applied to gearboxes and generators, although the effectiveness of these methods in detecting early signs of failure is not conclusive. If the cost of these systems can be reduced and the confidence in their detection ability improved, they may identify bearing problems at an early stage. This will allow staff to track the deterioration of gearboxes and generators so replacements can be scheduled during low-wind periods or coincidentally with other crane work.

7.3 Aftermarket Components

Common to any original equipment manufacturer (OEM) product, many of the parts used on a wind turbine are unique to the manufacturer and model. Wind turbine equipment has changed too rapidly, and equipment has been produced in too low volumes, to foster an aftermarket of major components. However, rebuild services for gearboxes, generators, and electrical components are available for older machines, although the advantages of economies of scale have not been realized. Potentially a mature aftermarket will develop to supply parts for the most recent phase of 700 to 2000 kW machines that have been installed in North America.

7.4 Innovative Rigging and Tooling

Much of the risk associated with failure of large wind turbine components is due to the uncertain cost of crane rental. Travel costs for a conventional crane that comprises 12 to 20 truckloads can be very high, especially for a remote site. Nacelle gantry cranes for generator removal are already available on some options. Alternate rigging and winching to remove blades, generators, and gearboxes could reduce both the cost and the risk to the project.

7.5 Recordkeeping

Extracting useful data from the available record was seriously limited by the inconsistency of the recording methods. The service logs and parts costs data were usually stored separately, which complicated the process of correlating costs with failure events. Projects would be well served by establishing a common recordkeeping system that allows failure events and associated costs to be easily extracted.

8. Conclusions

GEC has developed a tool for estimating O&M costs for wind energy projects. This model includes all the major cost contributors and is based on historical operating data from a variety of operating wind energy projects. The model was created in an Excel spreadsheet with a simple user interface and includes a range of generic turbines as examples.

The model estimates O&M costs over the 20-year life of the project, and allows the user to modify the project and turbine specifics. This tool should prove useful to project developers, owners, and operators in their evaluation of turbine and project options.

Appendix A

Using the O&M Cost Estimator Spreadsheet

Revision A, June 22, 2006

1.0 Overview

The workbook consists of six visible worksheets.
Sheet 1—Revisions. This sheet contains the latest revision information.
Sheet 2—Instructions.
Sheet 3—User Entry. Interface sheet for user input. You may enter values for any cells that are white. Gray cells cannot be edited, since they contain calculations or default values from field data. The default data are protected, so you can use macro buttons to return to default values.
Sheet 4—Results Tables. Tables and charts of results based on input values in the User Entry Sheet.
Sheet 5—Comparison Studies. Up to three sets of results from the Results Tables sheets may be captured with the macro buttons provided in the Results Tables sheet. A graphical summary chart at the top is provided for quick visual comparison of studies. Input values from the User Entry sheet are also captured, and may be reloaded into the User Entry Sheet by using macro buttons on each captured study.
Sheet 6—Failure and Cost Distribution. Constant failure rates or Weibull failure rates for each component are computed for the original parts. For Weibull failure distributions, failure rates are applied to replacement parts as well. Replacement or repair costs for each part are then calculated for each year of operation. The costs include crane costs, additional labor costs, and the part replacement costs shown on the User Entry Sheet.

2.0 Protection and Macros

Except for user input cells on the User Entry sheet, and some user cells on the Failure & Cost Distribution worksheet, all cells are protected within each worksheet. This prevents inadvertent modification of the supporting calculations and data.
Macros are used within the workbook, and must be enabled for the spreadsheet to function.

3.0 Getting Started—The User Entry Sheet

After reading the instructions and familiarizing yourself with the workbook, access the User Entry sheet. Adjust the screen size to see the entire width of the sheet. Beginning at the top of the sheet and working down, you can characterize the wind farm and populate cells with known O&M costs. Initial estimates from data have been provided as defaults, which should provide a reasonable degree of accuracy for initial modeling. *Refresh the* *default data if you change parameters in Tables 1 and 2* by clicking the "Use Default" macro buttons associated with each table in Tables 3 through 7. If you plan to use values other than default values, you should configure the wind farm and turbine tables first, refresh with defaults second, and then enter the custom values; otherwise, you will have default values from a prior configuration. A quick check with the default values to the right of each field will confirm whether you have updated your configuration with the Reset Default macro.

Some user notes appear on the User Entry worksheet that are reminders. You may add notes.

3.1 Table 1. Wind Farm Operations

Enter appropriate values for your study.

Capacity factor is used for determining the turbine operating costs per kWh (typically a range of 0.25 to 0.40 is used, depending on average site conditions expected for the 20-year period).

Energy sales price is currently used in the gross annual revenue calculation found in the Results Tables worksheet. The gross revenue is used merely as a relative reference to the O&M costs. Net revenue will not only be a function of O&M costs, but other costs not determined in the spreadsheet, such as land lease, insurance, taxes, etc.

3.2 Table 2. Wind Turbine Characteristics

Enter or select from the drop-down list appropriate values for your study.

Turbine rated power choices available are 750–2500 kW in increments of 50 kW. Default data from the Facility Costs worksheet is based on either 750, 1000, 1500, 2000, or 2500, whichever your value is closest to.

Power conversion choices are constant speed or variable speed. Default parts associated with each type of system are assigned quantities appropriate to the system. Parts not associated with each system will appear on the default parts list, but will have quantities of 0.

Pitch control choices available are hydraulic, electric, or fixed. All pitchable systems are assumed to be full span. Default parts associated with each type of system are assigned quantities appropriate to three-bladed turbines. Parts not associated with each system will appear on the default parts list, but will have quantities of 0.

Hub height is based on default values typical in the industry for each rating of turbine. Ultimately, tower height affects crane costs. If you are performing a comparison of O&M costs associated with various tower heights but do not have available crane cost data, you may manually enter the default value associated with each crane type or height found in the Facility Costs worksheet.

3.3 Table 3. Staffing Levels and Costs

Rates for manager, technician, and administrative assistant may be adjusted, as well as the burden, which accounts for additional costs above a negotiated salary or wage such as Social Security, medical, and retirement benefits. Administrator costs are annual salary values; technicians are hourly wages. To calculate hourly wages from an annual salary, divide the annual salary by 2080, which is a standard man-year.

3.4 Table 4. Annual Turbine Consumables

Default values are annual costs on a per turbine basis, and are driven by calendar rather than operating time. They are assumed to remain constant for 20 years using constant 2004 costs as a reference for default data.

Additional cells are provided for additional consumable items and costs.

3.5 Table 5. Crane Cost (+Mobilization)

Costs are driven to a large extent by mobilization, so you should obtain accurate data for the site. All parts replacements that require a crane assume the event is singular, rather than serial, and require a deployment for each failure except blade nonstructural repairs in the default parts list: all three blades are assumed to be repaired simultaneously with one mobilization.

Additional cells are provided for additional crane costs that are associated with a specific component. ***If you select "TRUE" for any parts that require a crane in the parts list, the component name and crane data need to be added to the crane costs table.*** To ensure correct lookup of the crane cost, you should use the "Update Table 5" macro button at the top of the column, and then enter the appropriate crane cost to Table 5 adjacent to any components without values to update the component title in the user cell.

3.6 Table 6. Site Equipment, Supplies, and Maintenance

You can supply your own values; however, site equipment and maintenance costs are small relative to the overall O&M costs.

Additional cells are provided for additional items.

3.7 Table 7. Turbine Parts List

Default values are based on field data. However, specific user data will provide more accurate results. If you choose to input different values, enter them in the user cells. Entering user values will override the default. To reset everything in the list to the default values, select the “default” macro button at the top of the table. A word of caution: You should copy the user values to a comparison study as a backup. If the user values are accidentally overwritten, the backup values can be reloaded.

You may select “Constant” or “Weibull” failure distributions. Many of the default data are based on Weibull Database failure distributions and correlated to available data. However, some failure rates of major components tend to be constant (and random), and are more accurately modeled with a constant failure rate. Operational experience will provide the best guidance.

You can study the effects of reduced part mean life by adjusting the Weibull “alpha” or “beta” parameters and looking at the adjacent mean life calculation.

The Miscellaneous parts category in the default parts list is used to account for all the remaining smaller components of the turbine. Ideally, each has a unique failure distribution. In reality, the overall effects of parts listed in this category are expected to be minor in relation to the other parts. As operators become more familiar with the characteristics of their parts, those with high failure rates may be added to the list as separate parts to investigate the cost effect on overall O&M.

4.0 Viewing and Saving Results

Initial results are best viewed by using the Results Tables tab. Each table and chart represents a different way of looking at the data.

To provide some comparison studies, you may save the results to the Comparison Studies worksheet by selecting the appropriate "capture" macro. Up to three studies can be compared at one time. *You should capture the initial study with all three macro buttons, so as not to have a study captured from prior use of the spreadsheet.* This is useful to evaluate the sensitivity of a serial part failure, or adjusted cost, such as a labor rate increase.

You should use the "Saved As" to save the file with an appropriate filename to protect a specific analysis.

5.0 Problem Notification and Enhancement Requests

We appreciate of any feedback you can provide. Your participation is very important, and can greatly improve the quality of the cost model for the entire user community.

Please e-mail any problems or requests for enhancement to the following address:
droberts@globalenergyconcepts.com
or
gec@globalenergyconcepts.com
attention: Task Code N12 Project Administrator
subject: Enhancement request or Problem notification

Appendix B

Part Quantities and Costs

Part Identification		New Cost from Data ($/unit)						Rebuild Cost Factor	$ / Event					
		Rating					New Cost Equation		Rating					
System	Component	750	1000	1500	2000	2500			750	1000	1500	2000	2500	Repair Description
Rotor	Blade--struct. repair	24,500	33,750	52,200	70,650	89,150	y = 73.892x - 6437.3	0.50	25,067	34,317	52,956	71,406	90,095	Structural fiber repair, replace with spare during repair
	Blade--nonstruct. repair	2,450	3,375	5,220	7,065	8,915	y = 73.892x - 6437.3	0.05	3,584	4,509	6,581	8,426	10,503	Cosmetic skin repair; drop rotor and repair 3 at a time
	Pitch cylinder & linkage	1,470	1,590	1,860	2,130	2,400	y = 1.8249x + 3482	0.30	1,583	1,779	2,087	2,395	2,702	Rebuild seals and servo
	Pitch bearing	6,200	9,700	16,700	23,700	30,700	y = 13.991x - 4263.3	1.00	7,145	10,645	17,834	24,834	32,023	Replace
	Pump & Hydraulics	3,780	3,780	3,780	3,780	3,780	y = 5400	0.70	3,931	3,931	3,931	3,931	3,931	Replace components only
	Pitch position xdcr	1,000	1,000	1,000	1,000	1,000	y = 1000	1.00	1,076	1,076	1,076	1,076	1,076	Replace
	Pitch motor	2,000	2,667	4,000	5,333	6,667	y = 4000*x/1500	1.00	2,076	2,742	4,076	5,409	6,742	Replace
	Pitch gear	1,015	1,353	2,030	2,707	3,383	y = 2900*x/1500	0.70	1,128	1,467	2,143	2,896	3,610	Rebuild, bearing replacement, refinish gears
	Pitch drive	2,100	2,800	4,200	5,600	7,000	y = 600*x/1500	0.70	2,176	2,876	4,276	5,676	7,076	Replace IGBTs, repair driver board
Drivetrain	Main bearing	4,500	7,100	13,400	21,000	29,800	y = .1472x1.5616	1.00	6,390	9,179	15,668	23,457	32,635	Replace
	High-speed coupling	2,045	2,727	4,091	5,455	6,818	y = 4500*x/1650	1.00	2,272	2,954	4,318	5,681	7,045	Replace
Gearbox and Lube	Gearbox--gear & brgs	65,030	92,470	151,900	216,020	283,850	y = 28.176x1.2237	0.70	66,353	93,982	153,601	217,910	286,118	Rebuild, bearing replacement, refinish gears
	Gearbox--brgs, all	37,160	52,840	86,800	123,440	162,200	y = 28.176x1.2237	0.40	38,483	54,352	88,501	125,330	164,468	Rebuild, bearing replacement
	Gearbox--high speed only	18,580	26,420	43,400	61,720	81,100	y = 28.176x1.2237	0.20	18,882	26,722	43,854	62,400	82,007	Rebuild HS side, bearing replacement
	Lube pumps	1,000	1,100	1,400	1,600	1,900	y = 1.55x + 1764.78	1.00	1,076	1,176	1,476	1,676	1,976	Replace
Generator and Cooling	Generator--rot. & brgs	16,800	28,840	52,850	76,860	100,870	y = 68.614x - 27416	0.70	17,102	29,180	53,228	77,276	101,324	Rebuild rotor windings, replace bearings
	Generator--brgs only	1,650	2,200	3,300	4,400	5,500	y = 2.2x	1.00	1,839	2,389	3,489	4,589	5,689	Replace bearings
	Power electronics	18,000	18,000	18,000	18,000	18,000	none, 1 data point	0.15	18,151	18,151	18,151	18,151	18,151	Replace IGBTs, repair driver board
	Motor, generator coolant fan	257	257	257	257	257	y = 285	0.90	332	332	332	332	332	Replace
	Contactor, generator	830	1,430	2,620	3,820	5,010	y = 2.3892x - 960.16	1.00	906	1,506	2,696	3,896	5,086	Replace
Brakes & Hydraulics	Brake caliper	1,170	1,230	1,370	1,500	1,630	y = 2.6579x + 9680.8	0.15	1,283	1,343	1,483	1,613	1,743	Replace seals
	Brake Pads	200	200	200	200	200	y = 200	1.00	200	200	200	200	200	Replace
	Accumulator	800	1,400	3,000	5,100	7,700	y = 0.0038x1.8563	1.00	876	1,476	3,076	5,176	7,776	Replace
	Hydraulic pump	1,200	1,200	1,200	1,200	1,200	y = 1200	1.00	1,276	1,276	1,276	1,276	1,276	Replace
	Hydraulic valve	120	120	120	120	120	y = 120	1.00	158	158	158	158	158	Replace
Yaw System	Yaw gear (drive+motor)	4,683	6,244	4,683	6,244	7,805	y = 17.883x/qty	0.70	4,834	6,395	4,834	6,395	7,956	Rebuild, bearing replacement, refinish gears
	Yaw caliper	250	250	250	250	250	y = 250	1.00	401	401	401	401	401	Replace seals
	Yaw sliding pads	400	400	400	400	400	y = 400	1.00	551	551	551	551	551	Replace
	Yaw bearing	2,850	4,102	6,853	9,863	13,083	y = 0.6535x^1.2659	1.00	4,740	6,181	9,121	12,320	15,918	Replace
Control System	Control board, Top	2,350	3,150	4,700	6,300	7,850	y =6.275x	0.50	2,350	3,150	4,700	6,300	7,850	Swapout with spare, repair board
	Control board, Main	2,900	3,950	6,000	8,100	10,200	y = 8.3429x - 471.43	0.50	2,900	3,950	6,000	8,100	10,200	Swapout with spare, repair board
	Control Module	580	790	1,200	1,620	2,040	y=0.2*Control Board Main	1.00	580	790	1,200	1,620	2,040	Replace
	Sensor, static	490	440	440	470	520	avg cost, y = 5.51x - 700.79: count, y = 15.637Ln(x) - 96.967	1.00	490	440	440	470	520	Replace
	Sensor, dynamic	1,200	1,200	1,200	1,200	1,200	y=1320	1.00	1,200	1,200	1,200	1,200	1,200	Replace
Electrical and Grid	Main Contactor	2,380	4,270	7,980	11,760	15,540	y = 10.715x - 4633.7	0.70	2,456	4,346	8,056	11,836	15,616	Swapout with spare, rebuild
	Main Circuit Breaker	1,484	3,087	8,687	18,074	31,920	y = 0.0001x2.5483	0.70	1,560	3,163	8,763	18,150	31,996	Swapout with spare, rebuild
	Soft starter	3,255	3,962	5,369	6,783	8,190	y = 4.0277x + 1630.6	0.70	3,406	4,113	5,520	6,934	8,341	Swapout with spare, rebuild
Misc. (All others)	Miscellaneous Parts	47,400	63,210	94,810	126,410	158,010	y = 63.205x	1.00	47,400	63,210	94,810	126,410	158,010	Replace

Appendix C

Failure Rate Assumptions

This appendix discusses the failure rate assumptions used in the model for selected components, along with GEC's rationale for selecting the Weibull parameters.

Gearbox

Determining the failure rates for a gearbox is complicated by the number of premature failures that have occurred with various newer wind turbines. The reasons for these failures are varied and are the subject of much controversy, but indications are that they are attributable to either manufacturing quality lapses or inappropriate design decisions. GEC does not believe that it is reasonable to project these very short lives into the future, and concludes that these problems will be, and in many cases have been, resolved.

Figure A-1 shows gearbox failures for a variety of turbines of sizes at different sites. In all cases, the year of failure is an average of a two or more year period. The trend line is a Weibull distribution through the seven non-premature failures, with a characteristic life of 27 years and a shape factor of 3.5. For comparison purposes, Vachon estimated a life of 12 to 20 years, but this estimate was based on pre-1999 machines. Industry characteristic life estimates for gears in general range from 12 to more than 100 years, with a typical value of 28 years.

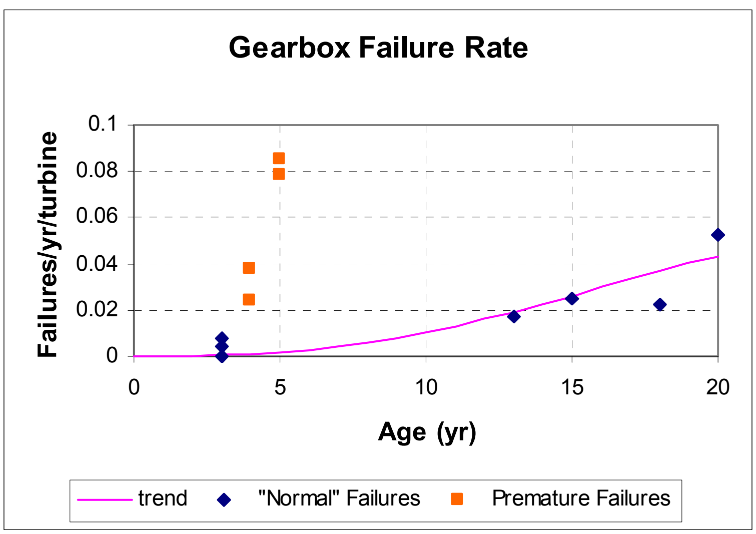


Figure C-1. Gearbox failure rates

Generator

Determining the failure rates for a generator is analogous to the difficulty with gearboxes; recently installed machines have exhibited a number of early failures, in two distinct modes. The first is winding failure, which may be the result of inadequate insulation systems or inappropriate winding design. The other failure mode is early bearing fatigue, which may be attributable to inappropriate fits or poor lubrication. GEC believes these problems are localized and in many cases have been rectified with design or manufacturing improvements, and that a mean life of 25 years with a shape factor of 3.5 is reasonable, as indicated with the trend line (see Figure A-2). This value is slightly less than the typical industry-wide mean life of 38 years for a motor, but is reasonable considering that the duty cycle and operating environment for a wind turbine generator are more severe than for a typical process motor.

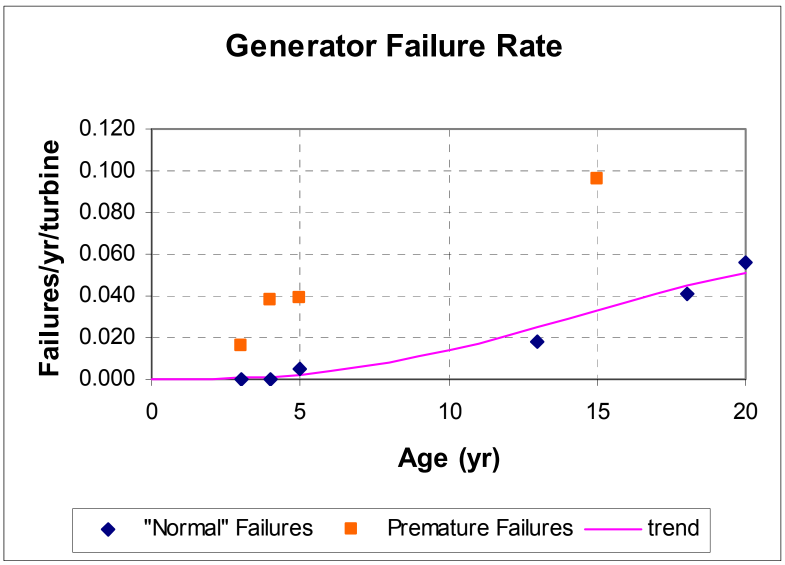


Figure C-2. Generator failure rates

Yaw Drive

The data available for yaw drive replacements are limited to the past 12 years. Before 1993, the turbines GEC evaluated used hydraulic yaw motors, whereas more modern machines use electric motor coupled to multistage reducers. The failure rate trend line presented in Figure A-3 uses a characteristic life of 12 years with a shape factor of 3.5. These values ignore the outlier point shown in the figure, which was assumed to be a serial replacement. The duty cycle on yaw drives may have increased since the introduction of sliding-pad type yaw bearings as opposed to the earlier low-friction ball bearings.

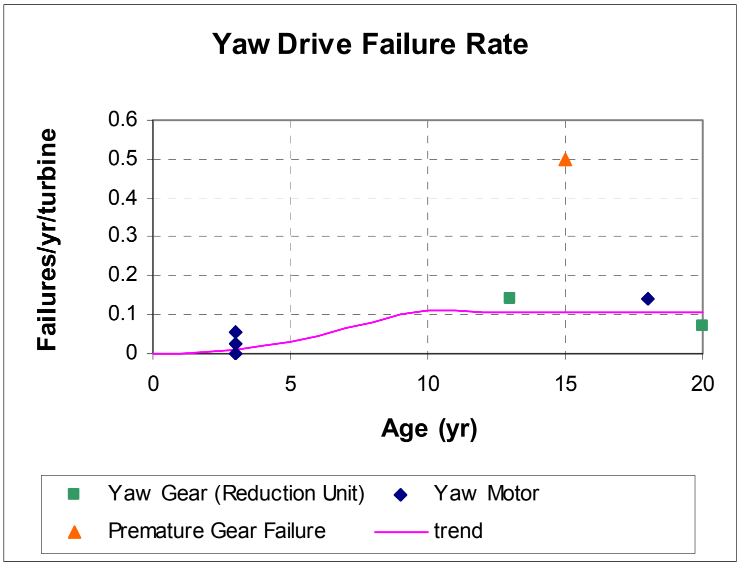


Figure C-3. Yaw drive failure rates

Pitch Cylinder

Minimal data were available for pitch cylinder failures, and it is not clear in which instances the cylinder was damaged irreparably. Figure A-4 shows a trend line for a characteristic life of 18 years with a shape factor of 2. However, GEC opted to use the vendor-proposed mean life of 10 years (Eta = 12, Beta =2). These values assume that seals will wear faster with the newer turbines than with the older styles because of the generally higher pitch activity demanded of modern pitch systems. The model assumes that the cylinder rod and body will last for the life of the turbine, but that the associated pitch servo valve will be replaced along with the seals.

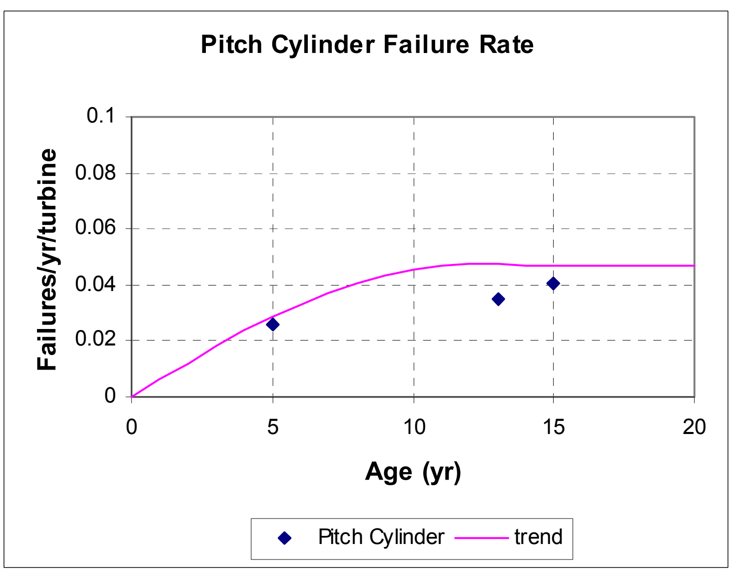


Figure C-4. Pitch cylinder failure rates

Contactors

The duty cycle for the contactors in a wind turbine varies widely depending on the device it is driving and the site conditions. Machines that come on and off line frequently, or with highly variable wind direction, will have a higher duty cycle and can expect contactors to wear faster. Airborne dust and contaminants can cause electromechanical equipment to degrade early. Based on the data in Figure A-5, GEC assumed a characteristic life of 20 years for all contactors. This is a higher value than is commonly encountered in other industries, but may be the result of a generally lower duty cycle. The generic turbines presented with the model assume that the turbines are fitted with well-sealed and filtered enclosures. Small contactors (e.g., for capacitor switching or pumps) are assumed to be replaced; main and bypass contactors are rebuilt.

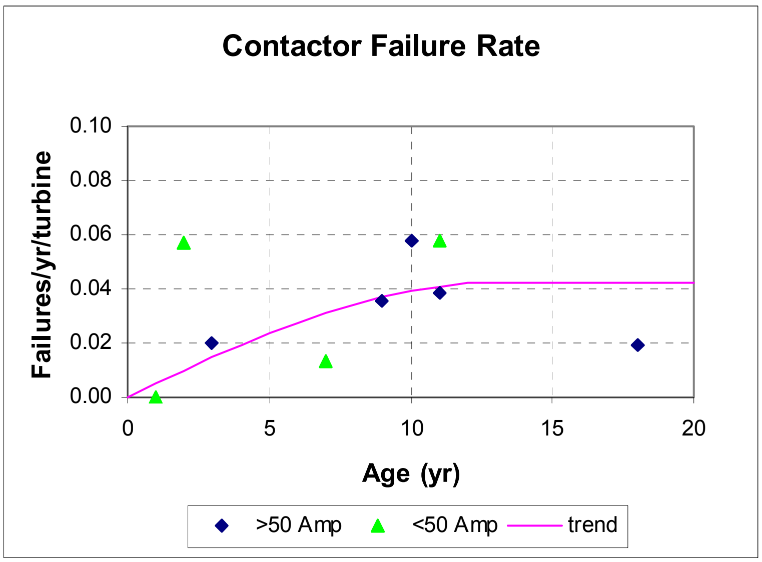


Figure C-5. Contactor failure rates

Controllers

All modern turbines use modular industrial-grade solid-state controllers that are hardened for use in vibration environments. Failure of these components is usually due to either thermal degradation or transient voltage surges. Figure A-6 presents data for several types of controller boards, both interface modules and central processors. The assumed trend line has a characteristic life of 15 years and a shape factor of 2. The model assumes that major components such as control processors are repairable, but interface modules are not.

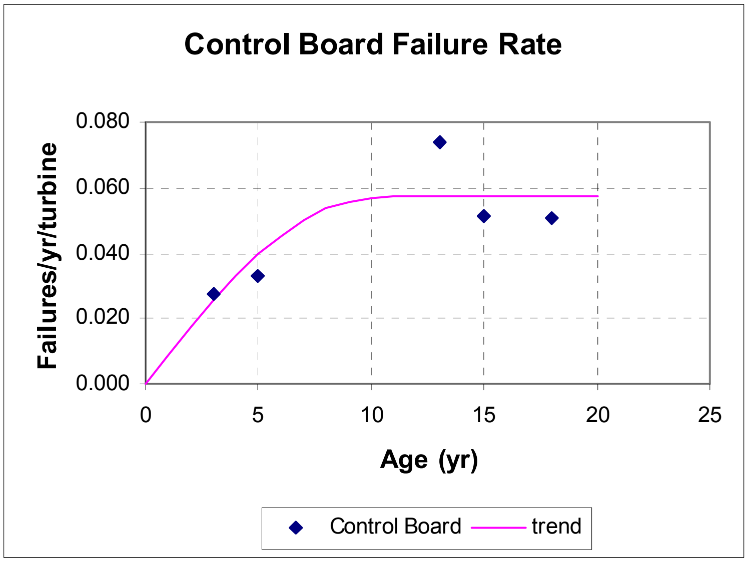


Figure C-6. Control board failure rates

Sensors

The useful life for all turbine sensors varies widely. As might be expected, thermal sensors, which have no moving parts, appear to last much longer than anemometers. Figure A-7 shows failure rates for all sensors, along with an assumed trend line with a characteristic life of 12 years and a shape factor of 2.

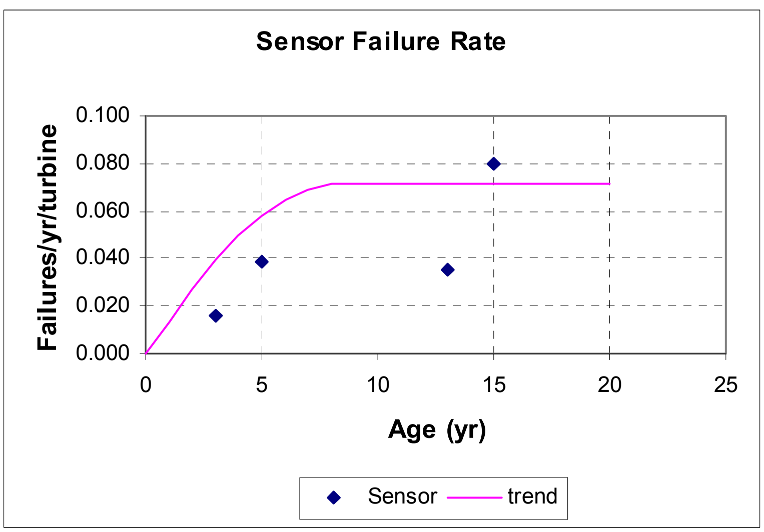


Figure C-7. Sensor failure rates

Appendix D

Model Results

750 kW model Results

Table 1. Wind Farm Operations	
Capacity Factor (%)	35
Number of Turbines	80
Energy Sales Price ($/kw-hr.)	0.055
Power Generated (MW)	60

Table 2. Turbine Characteristics	
Rating	750
Power Conversion	Constant Speed
Pitch Control	Hydraulic
Hub Height	60

Notes:

Description:	*750 kW, const. spd, hydraulic, 60m tower*

Table 3. Staffing Levels and Costs	*Salary ($/year) Wage ($/hr)*	*Burden (%)*	*Total*	*# of Staff* years 1-5	6-10	11-15	16-20	*Staffing Costs ($/Year)* years 1-5	6-10	11-15	16-20
Site Manager Salary	85,000	35	$ 114,750	1	1	1	1	114,750	114,750	114,750	114,750
Admin. Asst. Salary	35,000	35	$ 47,250	2	2	2	2	94,500	94,500	94,500	94,500
Sr. Tech Wage	18.00	35	$ 24.30	1	2	2	3	50,544	101,088	101,088	151,632
Jr. Tech Wage	12.00	35	$ 16.20	3	4	6	7	101,088	134,784	202,176	235,872
Totals								360,882	445,122	512,514	596,754

Table 4. Annual Turbine Consumables

Item	*User Values* *$/turbine*	*Default Values* *$/turbine*
Gear oil filter	100	100
Hydraulic filter	75	75
Offline-filter	100	100
Hydraulic oil replenish	20	20
Gear oil change (mineral)	145	145
Yaw gear grease	60	60
Bearing grease	45	45
Oil Testing	120	120
Electricity	657	657
Total	**1,322**	**1,322**

Table 5. Crane Cost (+Mobilization)

Item	**User** *$/event*	**Default** *$/event*
Blade--struct. repair	10,000	10,000
Blade--nonstruct. repai	10,000	10,000
Gearbox--gear & brgs	13,000	13,000
Gearbox--brgs, all	13,000	13,000
Gearbox--high speed c	13,000	13,000
Generator--rot. & brgs	8,000	8,000
Generator--brgs only	8,000	8,000
Main Bearing	13,000	13,000
Pitch Bearing	10,000	10,000
Yaw Bearing	13,000	13,000

Table 6. Site Equipment, Supplies & Maintenance

Annual Costs ($)

	User	*Default*
	$2,500	2,500
	$5,000	5,000
	$8,000	8,000
	$2,500	2,500
	$6,000	6,000
Total Equipment		**24,000**
	$5,000	5,000
	$4,100	4,100
	$2,500	2,500
	$1,700	1,700
	$800	800
Total Maintenance		**14,100**

Table 7. Turbine Parts List

Part Identification		Constant Failure Rate		Weibull Failure Rate			Repair/Replacement Costs				
System	**Component**	**Failure Prediction (Constant Rate or Weibull Curve)**	**Failures per 100 original parts by Year 20**	**Alpha**	**Beta**	**Mean Life (50% failures)**	**qty per turbine**	**Cost**	**Addt'l Labor to Repair / Replace (hr)**	**Crane?**	**Parts in Project**
Rotor	Blade--struct. repair	**Constant Rate**	5				3	24500	29	**TRUE**	240
	Blade--nonstruct. repair	**Constant Rate**	100				3	2450	59	**TRUE**	240
	Pitch cylinder & linkage	Weibull Curve		10	3.5	9.0	3	1470	7	FALSE	240
	Pitch bearing	Weibull Curve	5				3	6200	49	**TRUE**	240
	Pump & Hydraulics	Weibull Curve		12	3.5	10.8	1	3780	8	FALSE	80
	Pitch position xdcr	Weibull Curve		12	2.0	10.0	3	1000	4	FALSE	240
	Pitch motor	Weibull Curve		15	1.1	10.7	0	2000	4	FALSE	
	Pitch gear	Weibull Curve		12	3.5	10.8	0	1015	5	FALSE	
	Pitch drive	Weibull Curve		15	2.0	12.5	0	2100	4	FALSE	
Drivetrain	Main bearing	**Constant Rate**	5				1	4500	101	**TRUE**	80
	High-speed coupling	Weibull Curve		25	3.5	22.5	1	2045	12	FALSE	80
Gearbox and Lube	Gearbox--gear & brgs	**Constant Rate**	5				1	65030	71	**TRUE**	80
	Gearbox--brgs, all	Weibull Curve		20	3.5	18.0	1	37160	71	**TRUE**	80
	Gearbox--high speed only	Weibull Curve		20	3.5	18.0	1	18580	13	**TRUE**	80
	Lube pumps	Weibull Curve		12	3.0	10.6	3	1000	4	FALSE	240
	Cooling Fan, Gearbox Coo	Weibull Curve		19	1.1	13.6	1	257	4	FALSE	80
Generator and Cooling	Generator--rot. & brgs	**Constant Rate**	5				1	16800	16	**TRUE**	80
	Generator--brgs only	Weibull Curve		17	3.5	15.3	2	1650	10	**TRUE**	160
	Power electronics	Weibull Curve		15	2.0	12.5	0	18000	8	FALSE	
	Motor, generator coolant fa	Weibull Curve		19	1.1	13.6	1	257	4	FALSE	80
	Contactor, generator	Weibull Curve		20	2.0	16.7	3	830	4	FALSE	240
Brakes & Hydraulics	Brake caliper	Weibull Curve		10	2.0	8.3	2	1755	6	FALSE	160
	Brake Pads	**Constant Rate**	10				2	200	0	FALSE	160
	Accumulator	Weibull Curve		6	3.0	5.3	4	800	4	FALSE	320
	Hydraulic pump	Weibull Curve		12	3.0	10.6	1	1200	4	FALSE	80
	Hydraulic valve	Weibull Curve		12	3.0	10.6	3	120	2	FALSE	240
Yaw System	Yaw gear (drive+motor)	**Constant Rate**	5	12	3.5	10.8	2	4683	8	FALSE	160
	Yaw caliper	Weibull Curve		10	2.0	8.3	2	250	8	FALSE	160
	Yaw sliding pads	Weibull Curve		10	3.5	9.0	4	400	8	FALSE	320
	Yaw bearing	Weibull Curve	0				1	2850	101	**TRUE**	80
Control System	Control board, Top	Weibull Curve		15	2.0	12.5	1	2350	0	FALSE	80
	Control board, Main	Weibull Curve		15	2.0	12.5	1	2900	0	FALSE	80
	Control Module	Weibull Curve		15	2.0	12.5	4	580	0	FALSE	320
	Sensor, static	Weibull Curve		14	2.0	11.7	7	140	0	FALSE	560
	Sensor, dynamic	Weibull Curve		12	2.0	10.0	4	1200	0	FALSE	320
Electrical and Grid	Main Contactor	Weibull Curve		20	2.0	16.7	1	2380	4	FALSE	80
	Main Circuit Breaker	Weibull Curve		30	2.0	25.0	1	1484	4	FALSE	80
	Soft starter	Weibull Curve		30	2.0	25.0	0	3255	8	FALSE	
Misc. (All others)	Miscellaneous Parts	**Constant Rate**	5				1	47400	0	FALSE	80

750 kW Results

Entry Values	
Turbine Rated Power (kW)	750
Pitch Systmem	Hydraulic
Rotor Speed Control	Constant Speed
Turbine Quantity	80
Total Project Power (MW)	60
Project Capacity Factor	0.35

Project Parts Cost Breakdown	
Parts	9,879,414
Crane	3,036,500
Additional Labor	843194
Total	13,759,107

Gross Project Income / yr	Gross Turbine Income / yr	Annual Production (MW-hr)
$10,117,800	$126,473	$183,960

Total Project O&M Cost ($000)

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Total
Parts Replacement (Hardware	106	188	207	297	489	451	544	541	700	863	786	932	809	1013	1058	982	1099	979	1107	1125	257	620	919	1058	14275
Consumables	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	2116
Salaried Labor	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	4185
Wage-based Labor	152	152	152	152	152	236	236	236	236	236	303	303	303	303	303	388	388	388	388	388	152	236	303	388	5391
Site Maintenance	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	282
Equipment	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	480
Total	611	693	711	802	994	1040	1133	1130	1289	1452	1442	1588	1466	1669	1714	1723	1839	1720	1847	1865	762	1209	1576	1799	26729

O&M $ /Turbine

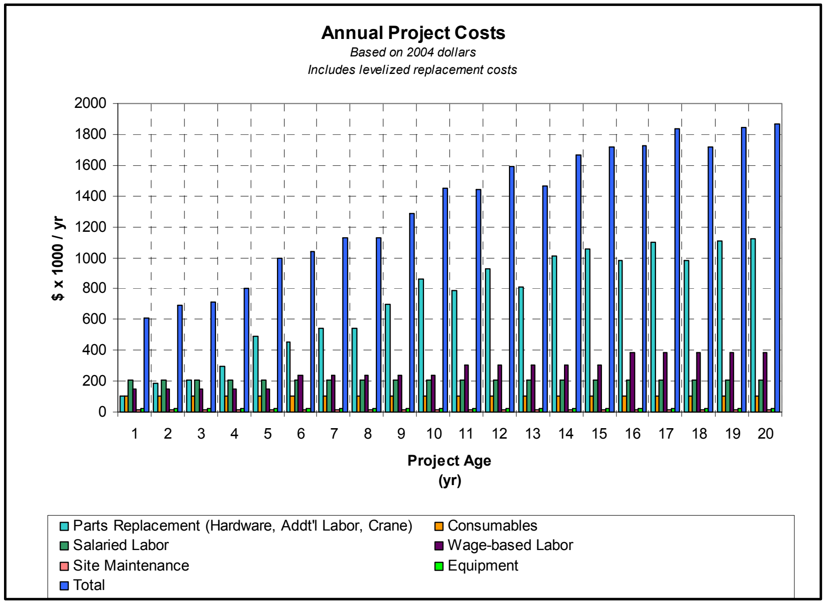
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	yr 1-5	yr 6-10	15	20	20 yr Avg
Parts Replacement (Hardware	1323	2355	2583	3718	6111	5635	6806	6757	8749	10790	9822	11644	10117	12658	13222	12276	13735	12240	13832	14060	3218	7748	11493	13228	8922
Consumables	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322	1322
Salaried Labor	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616	2616
Wage-based Labor	1895	1895	1895	1895	1895	2948	2948	2948	2948	2948	3791	3791	3791	3791	3791	4844	4844	4844	4844	4844	1895	2948	3791	4844	3370
Site Maintenance	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176
Equipment	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Total	7633	8665	8893	10028	12421	12998	14169	14120	16112	18153	18027	19849	18322	20863	21427	21534	22993	21498	23090	23318	9528	15110	19698	22486	16706

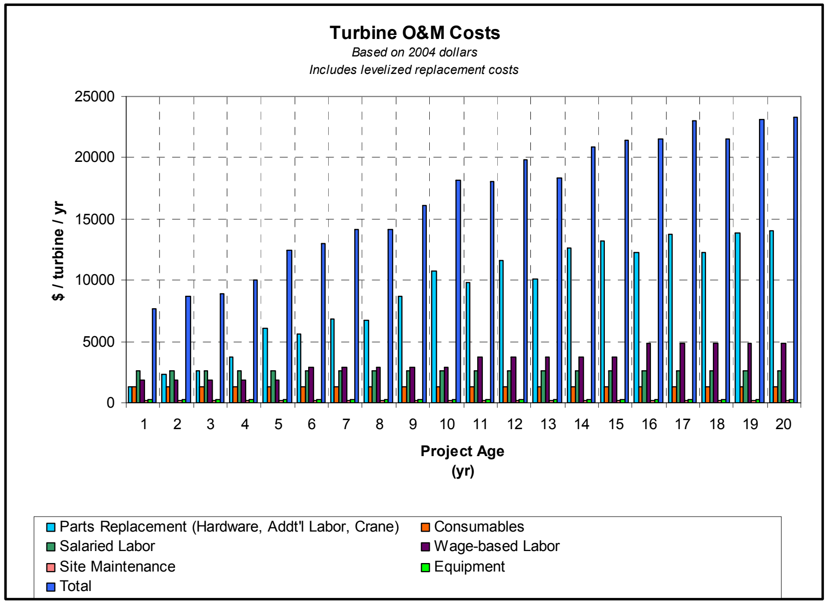
O&M $ /kW

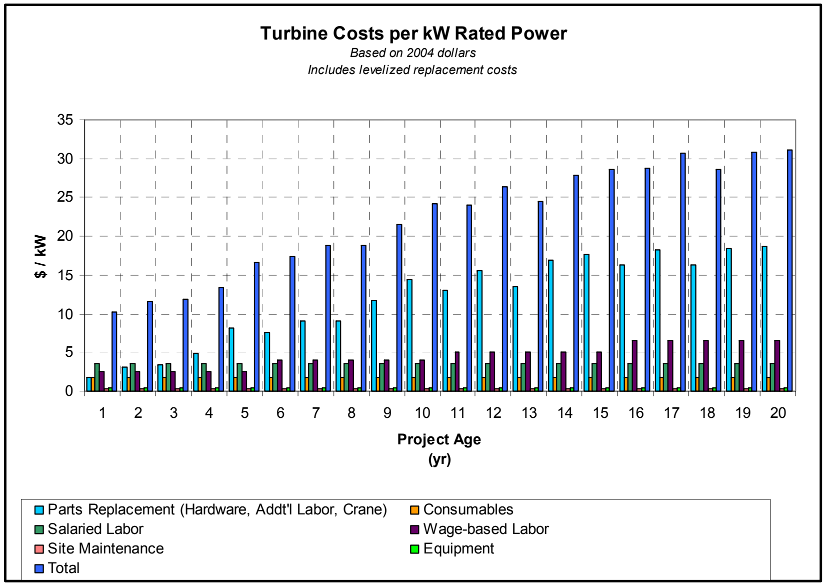
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	1.8	3.1	3.4	5.0	8.1	7.5	9.1	9.0	11.7	14.4	13.1	15.5	13.5	16.9	17.6	16.4	18.3	16.3	18.4	18.7	4.3	10.3	15.3	17.6	11.90
Consumables	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.76
Salaried Labor	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.49
Wage-based Labor	2.5	2.5	2.5	2.5	2.5	3.9	3.9	3.9	3.9	3.9	5.1	5.1	5.1	5.1	5.1	6.5	6.5	6.5	6.5	6.5	2.5	3.9	5.1	6.5	4.49
Site Maintenance	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.24
Equipment	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.40
Total	10.2	11.6	11.9	13.4	16.6	17.3	18.9	18.8	21.5	24.2	24.0	26.5	24.4	27.8	28.6	28.7	30.7	28.7	30.8	31.1	12.7	20.1	26.3	30.0	22.27

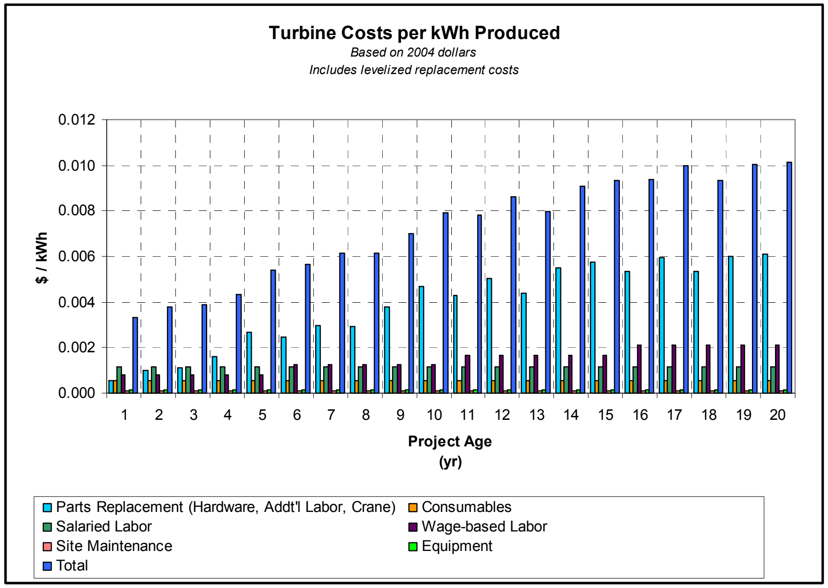
O&M $ /kWh

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	0.001	0.001	0.001	0.002	0.003	0.002	0.003	0.003	0.004	0.005	0.004	0.005	0.004	0.006	0.006	0.005	0.006	0.005	0.006	0.006	0.00	0.00	0.00	0.01	0.00
Consumables	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Salaried Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Wage-based Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.00	0.00	0.00	0.00	0.00
Site Maintenance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Equipment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Total	0.003	0.004	0.004	0.004	0.005	0.006	0.006	0.006	0.007	0.008	0.008	0.009	0.008	0.009	0.009	0.009	0.010	0.009	0.010	0.010	0.00	0.01	0.01	0.01	0.01


Annual Project Costs
Based on 2004 dollars
Includes levelized replacement costs
$ x 1000 / yr
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine O&M Costs
Based on 2004 dollars
Includes levelized replacement costs
$ / turbine / yr
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kW Rated Power
Based on 2004 dollars
Includes levelized replacement costs
$ / kW
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kWh Produced
Based on 2004 dollars
Includes levelized replacement costs
$ / kWh
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total

1000 kW model Results

Table 1. Wind Farm Operations	
Capacity Factor (%)	35
Number of Turbines	60
Energy Sales Price ($/kw-hr.)	0.055
Power Generated (MW)	60

Table 2. Turbine Characteristics	
Rating	1000
Power Conversion	Constant Speed
Pitch Control	Hydraulic
Hub Height	65

Notes:	
Description:	*1000 kW, const. spd, hydraulic, 65m tower*

Table 3. Staffing Levels and Costs	*Salary ($/year)* *Wage ($/hr)*	*Burden* *(%)*		*Total*	*# of Staff* years 1-5	6-10	11-15	16-20	*Staffing Costs ($/Year)* years 1-5	6-10	11-15	16-20
Site Manager Salary	85,000	35	$	114,750	1	1	1	1	114,750	114,750	114,750	114,750
Admin. Asst. Salary	35,000	35	$	47,250	2	2	2	2	94,500	94,500	94,500	94,500
Sr. Tech Wage	18.00	35	$	24.30	1	1	2	2	50,544	50,544	101,088	101,088
Jr. Tech Wage	12.00	35	$	16.20	2	4	4	6	67,392	134,784	134,784	202,176
Totals									327,186	394,578	445,122	512,514

Table 4. Annual Turbine Consumables *Item*	*User Values* *$/turbine*	*Default Values* *$/turbine*
Gear oil filter	133	133
Hydraulic filter	100	100
Offline-filter	100	100
Hydraulic oil replenish	20	20
Gear oil change (mineral)	192	192
Yaw gear grease	80	80
Bearing grease	60	60
Oil Testing	120	120
Electricity	876	876
Total	**1,681**	**1,681**

Table 5. Crane Cost (+Mobilization) *Item*	**User** *$/event*	**Default** *$/event*
Blade--struct. repair	14,000	14,000
Blade--nonstruct. repai	14,000	14,000
Gearbox--gear & brgs	23,000	23,000
Gearbox--brgs, all	23,000	23,000
Gearbox--high speed c	23,000	23,000
Generator--rot. & brgs	15,000	15,000
Generator--brgs only	15,000	15,000
Main Bearing	23,000	23,000
Pitch Bearing	14,000	14,000
Yaw Bearing	23,000	23,000

Table 6. Site Equipment, Supplies & Maintenance Annual Costs ($)	*User*	*Default*
	$2,500	2,500
	$5,000	5,000
	$8,000	8,000
	$2,500	2,500
	$6,000	6,000
	Total Equipment	**24,000**
	$5,000	5,000
	$4,100	4,100
	$2,500	2,500
	$1,700	1,700
	$800	800
	Total Maintenance	**14,100**

Table 7. Turbine Parts List

Part Identification		Constant Failure Rate		Weibull Failure Rate			Repair/Replacement Costs				
System	Component	Failure Prediction (Constant Rate or Weibull Curve)	Failures per 100 original parts by Year 20	Alpha	Beta	Mean Life (50% failures)	qty per turbine	Cost	Addt'l Labor to Repair / Replace (hr)	Crane?	Parts in Project
Rotor	Blade--struct. repair	**Constant Rate**	5				3	33750	32	**TRUE**	180
	Blade--nonstruct. repair	**Constant Rate**	100				3	3375	62	**TRUE**	180
	Pitch cylinder & linkage	Weibull Curve		10	3.5	9.0	3	1590	9	FALSE	180
	Pitch bearing	Weibull Curve	5				3	9700	52	**TRUE**	180
	Pump & Hydraulics	Weibull Curve		12	3.5	10.8	1	3780	8	FALSE	60
	Pitch position xdcr	Weibull Curve		12	2.0	10.0	3	1000	4	FALSE	180
	Pitch motor	Weibull Curve		15	1.1	10.7	0	2667	4	FALSE	
	Pitch gear	Weibull Curve		12	3.5	10.8	0	1353	6	FALSE	
	Pitch drive	Weibull Curve		15	2.0	12.5	0	2800	4	FALSE	
Drivetrain	Main bearing	**Constant Rate**	5				1	7100	107	**TRUE**	60
	High-speed coupling	Weibull Curve		25	3.5	22.5	1	2727	12	FALSE	60
Gearbox and Lube	Gearbox--gear & brgs	**Constant Rate**	5				1	92470	77	**TRUE**	60
	Gearbox--brgs, all	Weibull Curve		20	3.5	18.0	1	52840	77	**TRUE**	60
	Gearbox--high speed only	Weibull Curve		20	3.5	18.0	1	26420	18	**TRUE**	60
	Lube pumps	Weibull Curve		12	3.0	10.6	3	1100	4	FALSE	180
	Cooling Fan, Gearbox Coo	Weibull Curve		19	1.1	13.6	2	257	4	FALSE	120
Generator and Cooling	Generator--rot. & brgs	**Constant Rate**	5				1	28840	18	**TRUE**	60
	Generator--brgs only	Weibull Curve		17	3.5	15.3	2	2200	10	**TRUE**	120
	Power electronics	Weibull Curve		15	2.0	12.5	0	18000	8	FALSE	
	Motor, generator coolant fa	Weibull Curve		19	1.1	13.6	2	257	4	FALSE	120
	Contactor, generator	Weibull Curve		20	2.0	16.7	3	1430	4	FALSE	180
Brakes & Hydraulics	Brake caliper	Weibull Curve		10	2.0	8.3	2	1845	6	FALSE	120
	Brake Pads	**Constant Rate**	10				2	200	0	FALSE	120
	Accumulator	Weibull Curve		6	3.0	5.3	4	1400	4	FALSE	240
	Hydraulic pump	Weibull Curve		12	3.0	10.6	1	1200	4	FALSE	60
	Hydraulic valve	Weibull Curve		12	3.0	10.6	3	120	2	FALSE	180
Yaw System	Yaw gear (drive+motor)	**Constant Rate**	5	12	3.5	10.8	2	6244	8	FALSE	120
	Yaw caliper	Weibull Curve		10	2.0	8.3	2	250	8	FALSE	120
	Yaw sliding pads	Weibull Curve		10	3.5	9.0	4	400	8	FALSE	240
	Yaw bearing	Weibull Curve	0				1	4102	107	**TRUE**	60
Control System	Control board, Top	Weibull Curve		15	2.0	12.5	1	3150	0	FALSE	60
	Control board, Main	Weibull Curve		15	2.0	12.5	1	3950	0	FALSE	60
	Control Module	Weibull Curve		15	2.0	12.5	4	790	0	FALSE	240
	Sensor, static	Weibull Curve		14	2.0	11.7	11	190	0	FALSE	660
	Sensor, dynamic	Weibull Curve		12	2.0	10.0	4	1200	0	FALSE	240
Electrical and Grid	Main Contactor	Weibull Curve		20	2.0	16.7	1	4270	4	FALSE	60
	Main Circuit Breaker	Weibull Curve		30	2.0	25.0	1	3087	4	FALSE	60
	Soft starter	Weibull Curve		30	2.0	25.0	0	3962	8	FALSE	
Misc. (All others)	Miscellaneous Parts	**Constant Rate**	5				1	63210	0	FALSE	60

1000 kW Results

Entry Values	
Turbine Rated Power (kW)	1000
Pitch Systmem	Hydraulic
Rotor Speed Control	Constant Speed
Turbine Quantity	60
Total Project Power (MW)	60
Project Capacity Factor	0.35

Project Parts Cost Breakdown	
Parts	9,716,424
Crane	4,006,200
Additional Labor	668477
Total	14,391,101

Gross Project Income / yr	Gross Turbine Income / yr	Annual Production (MW-hr)
$10,117,800	$168,630	$183,960

Total Project O&M Cost ($000)

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Total
Parts Replacement (Hardware	104	150	248	275	360	499	645	580	773	655	778	987	951	1196	1080	1007	1085	1139	1074	1326	227	630	998	1126	14912
Consumables	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	2017
Salaried Labor	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	4185
Wage-based Labor	118	118	118	118	118	185	185	185	185	185	236	236	236	236	236	303	303	303	303	303	118	185	236	303	4212
Site Maintenance	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	282
Equipment	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	480
Total	570	616	714	742	826	1032	1178	1113	1307	1189	1362	1571	1535	1780	1664	1659	1736	1790	1726	1978	694	1164	1583	1778	26088

O&M $ /Turbine

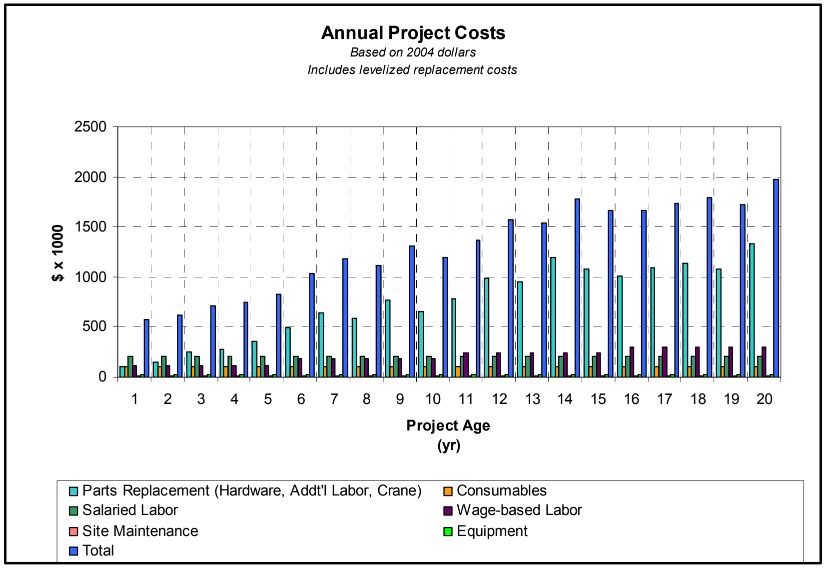
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	1732	2493	4133	4589	6001	8313	10746	9664	12887	10917	12963	16457	15845	19934	18005	16787	18078	18982	17906	22101	3790	10505	16641	18771	12427
Consumables	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681	1681
Salaried Labor	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488	3488
Wage-based Labor	1966	1966	1966	1966	1966	3089	3089	3089	3089	3089	3931	3931	3931	3931	3931	5054	5054	5054	5054	5054	1966	3089	3931	5054	3510
Site Maintenance	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235	235
Equipment	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Total	9501	10263	11902	12358	13770	17205	19638	18556	21779	19809	22698	26192	25580	29668	27740	27645	28936	29840	28764	32959	11559	19398	26376	29629	21740

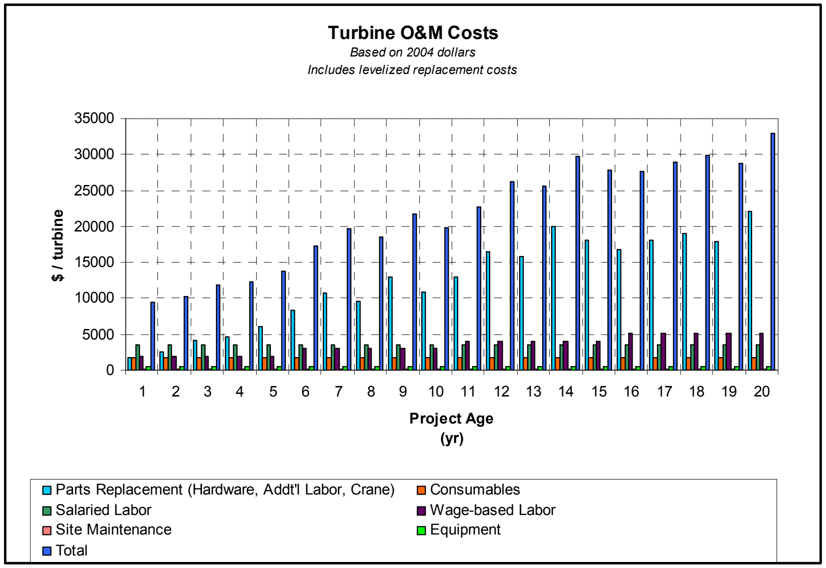
O&M $ /kW

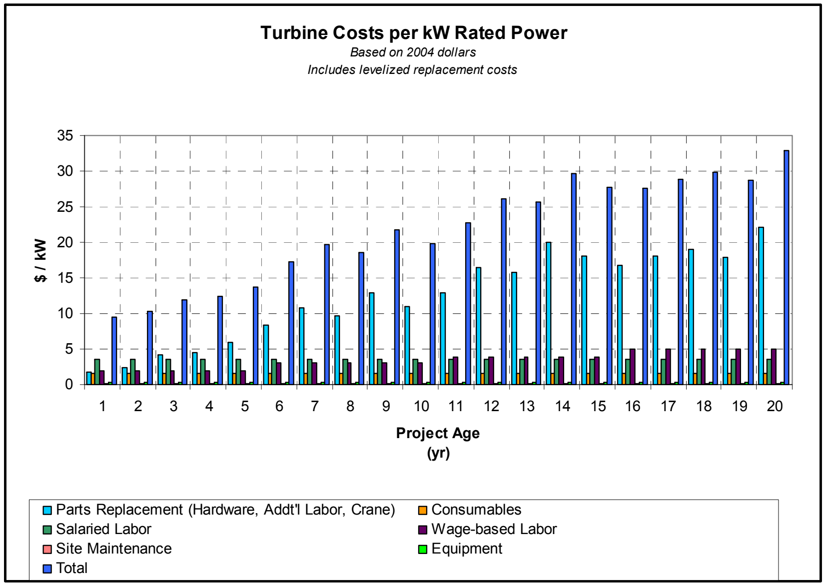
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	1.7	2.5	4.1	4.6	6.0	8.3	10.7	9.7	12.9	10.9	13.0	16.5	15.8	19.9	18.0	16.8	18.1	19.0	17.9	22.1	3.8	10.5	16.6	18.8	12.43
Consumables	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.68
Salaried Labor	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.49
Wage-based Labor	2.0	2.0	2.0	2.0	2.0	3.1	3.1	3.1	3.1	3.1	3.9	3.9	3.9	3.9	3.9	5.1	5.1	5.1	5.1	5.1	2.0	3.1	3.9	5.1	3.51
Site Maintenance	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.24
Equipment	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.40
Total	9.5	10.3	11.9	12.4	13.8	17.2	19.6	18.6	21.8	19.8	22.7	26.2	25.6	29.7	27.7	27.6	28.9	29.8	28.8	33.0	11.6	19.4	26.4	29.6	21.74

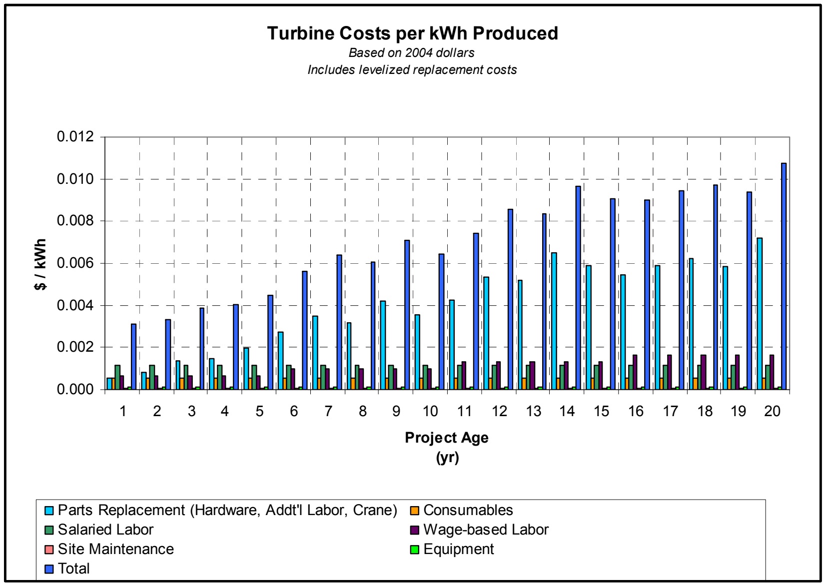
O&M $ /kWh

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	0.001	0.001	0.001	0.001	0.002	0.003	0.004	0.003	0.004	0.004	0.004	0.005	0.005	0.007	0.006	0.005	0.006	0.006	0.006	0.007	0.00	0.00	0.01	0.01	0.00
Consumables	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Salaried Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Wage-based Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.00	0.00	0.00	0.00	0.00
Site Maintenance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Equipment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Total	0.003	0.003	0.004	0.004	0.004	0.006	0.006	0.006	0.007	0.006	0.007	0.009	0.008	0.010	0.009	0.009	0.009	0.010	0.009	0.011	0.00	0.01	0.01	0.01	0.01


Annual Project Costs
Based on 2004 dollars
Includes levelized replacement costs
$ x 1000
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine O&M Costs
Based on 2004 dollars
Includes levelized replacement costs
$ / turbine
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kW Rated Power
Based on 2004 dollars
Includes levelized replacement costs
$ / kW
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kWh Produced
Based on 2004 dollars
Includes levelized replacement costs
$ / kWh
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total

1500 kW model Results

Table 1. Wind Farm Operations	
Capacity Factor (%)	35
Number of Turbines	40
Energy Sales Price ($/kw-hr.)	0.055
Power Generated (MW)	60

Notes:	
Description:	*1500 kW, var. speed, electric 80m tower*

Table 2. Turbine Characteristics	
Rating	1500
Power Conversion	Variable Speed
Pitch Control	Electric
Hub Height	80

Table 3. Staffing Levels and Costs	*Salary ($/year)* *Wage ($/hr)*	*Burden (%)*		*Total*	# of Staff years 1-5	6-10	11-15	16-20	Staffing Costs ($/Year) years 1-5	6-10	11-15	16-20
Site Manager Salary	85,000	35	$	114,750	1	1	1	1	114,750	114,750	114,750	114,750
Admin. Asst. Salary	35,000	35	$	47,250	2	2	2	2	94,500	94,500	94,500	94,500
Sr. Tech Wage	18.00	35	$	24.30	1	1	2	2	50,544	50,544	101,088	101,088
Jr. Tech Wage	12.00	35	$	16.20	3	4	4	5	101,088	134,784	134,784	168,480
Totals									360,882	394,578	445,122	478,818

Table 4. Annual Turbine Consumables *Item*	*User Values $/turbine*	*Default Values $/turbine*
Gear oil filter	200	200
Hydraulic filter	100	100
Offline-filter	100	100
Hydraulic oil replenish	20	20
Gear oil change (mineral)	284	284
Yaw gear grease	120	120
Bearing grease	90	90
Oil Testing	120	120
Electricity	1,314	1,314
Total	**2,348**	**2,348**

Table 5. Crane Cost (+Mobilization) *Item*	**User** *$/event*	**Default** *$/event*
Blade--struct. repair	28,000	28,000
Blade--nonstruct. repai	28,000	28,000
Gearbox--gear & brgs	56,000	56,000
Gearbox--brgs, all	56,000	56,000
Gearbox--high speed c	56,000	56,000
Generator--rot. & brgs	39,000	39,000
Generator--brgs only	39,000	39,000
Main Bearing	56,000	56,000
Pitch Bearing	28,000	28,000
Yaw Bearing	56,000	56,000

Table 6. Site Equipment, Supplies & Maintenance Annual Costs ($)	*User*	*Default*
	$2,500	2,500
	$5,000	5,000
	$8,000	8,000
	$2,500	2,500
	$6,000	6,000
Total Equipment		**24,000**
	$5,000	5,000
	$4,100	4,100
	$2,500	2,500
	$1,700	1,700
	$800	800
Total Maintenance		**14,100**

Table 7. Turbine Parts List

Part Identification		Constant Failure Rate		Weibull Failure Rate			Repair/Replacement Costs				
System	Component	Failure Prediction (Constant Rate or Weibull Curve)	Failures per 100 original parts by Year 20	Alpha	Beta	Mean Life (50% failures)	qty per turbine	Cost	Addt'l Labor to Repair / Replace (hr)	Crane?	Parts in Project
Rotor	Blade--struct. repair	**Constant Rate**	5				3	52200	37	**TRUE**	120
	Blade--nonstruct. repair	**Constant Rate**	100				3	5220	69	**TRUE**	120
	Pitch cylinder & linkage	Weibull Curve		10	3.5	9.0	0	1860	11	FALSE	
	Pitch bearing	Weibull Curve	5				3	16700	57	**TRUE**	120
	Pump & Hydraulics	Weibull Curve		12	3.5	10.8	0	3780	8	FALSE	
	Pitch position xdcr	Weibull Curve		12	2.0	10.0	0	1000	4	FALSE	
	Pitch motor	Weibull Curve		15	1.1	10.7	3	4000	4	FALSE	120
	Pitch gear	Weibull Curve		12	3.5	10.8	3	2030	8	FALSE	120
	Pitch drive	Weibull Curve		15	2.0	12.5	3	4200	4	FALSE	120
Drivetrain	Main bearing	**Constant Rate**	5				1	13400	121	**TRUE**	40
	High-speed coupling	Weibull Curve		25	3.5	22.5	1	4091	12	FALSE	40
Gearbox and Lube	Gearbox--gear & brgs	**Constant Rate**	5				1	151900	91	**TRUE**	40
	Gearbox--brgs, all	Weibull Curve		20	3.5	18.0	1	86800	91	**TRUE**	40
	Gearbox--high speed only	Weibull Curve		20	3.5	18.0	1	43400	27	**TRUE**	40
	Lube pumps	Weibull Curve		12	3.0	10.6	3	1400	4	FALSE	120
	Cooling Fan, Gearbox Coo	Weibull Curve		19	1.1	13.6	2	257	4	FALSE	80
Generator and Cooling	Generator--rot. & brgs	**Constant Rate**	5				1	52850	20	**TRUE**	40
	Generator--brgs only	Weibull Curve		17	3.5	15.3	2	3300	10	**TRUE**	80
	Power electronics	Weibull Curve		15	2.0	12.5	1	18000	8	FALSE	40
	Motor, generator coolant fa	Weibull Curve		19	1.1	13.6	2	257	4	FALSE	80
	Contactor, generator	Weibull Curve		20	2.0	16.7	3	2620	4	FALSE	120
Brakes & Hydraulics	Brake caliper	Weibull Curve		10	2.0	8.3	3	2055	6	FALSE	120
	Brake Pads	**Constant Rate**	10				2	200	0	FALSE	80
	Accumulator	Weibull Curve		6	3.0	5.3	1	3000	4	FALSE	40
	Hydraulic pump	Weibull Curve		12	3.0	10.6	1	1200	4	FALSE	40
	Hydraulic valve	Weibull Curve		12	3.0	10.6	4	120	2	FALSE	160
Yaw System	Yaw gear (drive+motor)	**Constant Rate**	5	12	3.5	10.8	4	9359	8	FALSE	160
	Yaw caliper	Weibull Curve		10	2.0	8.3	4	250	8	FALSE	160
	Yaw sliding pads	Weibull Curve		10	3.5	9.0	8	400	8	FALSE	320
	Yaw bearing	Weibull Curve	0				1	6853	121	**TRUE**	40
Control System	Control board, Top	Weibull Curve		15	2.0	12.5	1	4700	0	FALSE	40
	Control board, Main	Weibull Curve		15	2.0	12.5	1	6000	0	FALSE	40
	Control Module	Weibull Curve		15	2.0	12.5	2	1200	0	FALSE	80
	Sensor, static	Weibull Curve		14	2.0	11.7	17	300	0	FALSE	680
	Sensor, dynamic	Weibull Curve		12	2.0	10.0	2	1200	0	FALSE	80
Electrical and Grid	Main Contactor	Weibull Curve		20	2.0	16.7	1	7980	4	FALSE	40
	Main Circuit Breaker	Weibull Curve		30	2.0	25.0	1	8687	4	FALSE	40
	Soft starter	Weibull Curve		30	2.0	25.0	0	5369	8	FALSE	
Misc. (All others)	Miscellaneous Parts	**Constant Rate**	5				1	94810	0	FALSE	40

1500 kW Results

Entry Values	
Turbine Rated Power (kW)	1500
Pitch Systmem	Electric
Rotor Speed Control	Variable Speed
Turbine Quantity	40
Total Project Power (MW)	60
Project Capacity Factor	0.35

Project Parts Cost Breakdown	
Parts	10,421,675
Crane	6,575,400
Additional Labor	518531
Total	17,515,606

Gross Project Income / yr	Gross Turbine Income / yr	Annual Production (MW-hr)
$10,117,800	$252,945	$183,960

Total Project O&M Cost ($000)

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Total
Parts Replacement (Hardware	134	197	235	338	363	363	765	475	799	1315	1109	1151	942	1508	1229	1426	1292	1482	1429	1601	253	744	1188	1446	18154
Consumables	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	1879
Salaried Labor	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	4185
Wage-based Labor	152	152	152	152	152	185	185	185	185	185	236	236	236	236	236	270	270	270	270	270	152	185	236	270	4212
Site Maintenance	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	282
Equipment	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	480
Total	627	690	728	831	855	890	1292	1002	1325	1842	1686	1728	1519	2085	1807	2037	1903	2093	2040	2212	746	1270	1765	2057	29192

O&M $ /Turbine

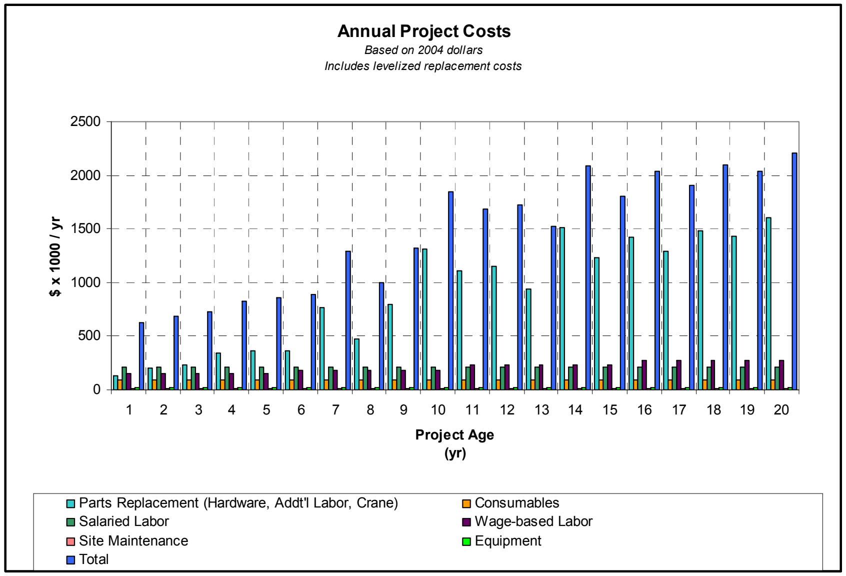
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	3360	4922	5878	8443	9065	9081	19135	11880	19969	32875	27721	28781	23540	37700	30735	35646	32309	37060	35730	40027	6333	18588	29695	36154	22693
Consumables	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348	2348
Salaried Labor	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231	5231
Wage-based Labor	3791	3791	3791	3791	3791	4633	4633	4633	4633	4633	5897	5897	5897	5897	5897	6739	6739	6739	6739	6739	3791	4633	5897	6739	5265
Site Maintenance	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353	353
Equipment	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
Total	15683	17245	18200	20766	21387	22246	32300	25045	33134	46040	42150	43210	37968	52129	45164	50917	47580	52331	51001	55299	18656	31753	44124	51426	36490

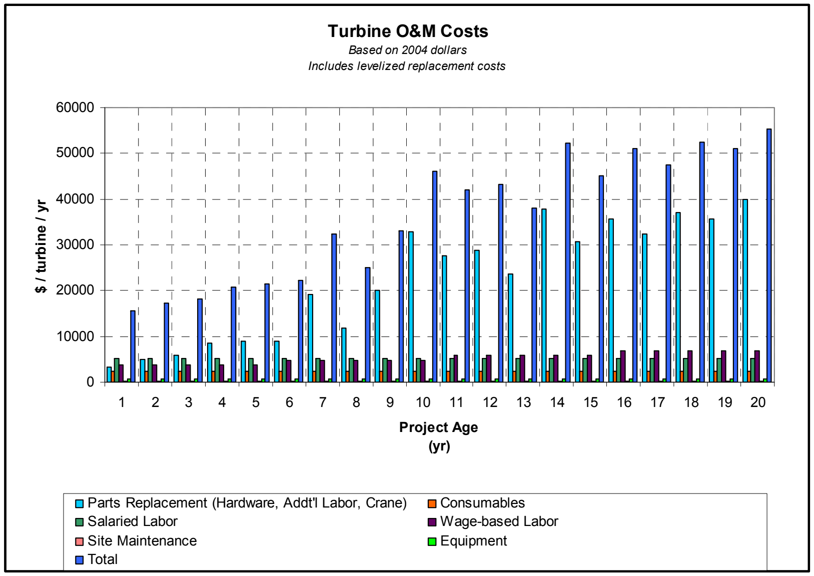
O&M $ /kW

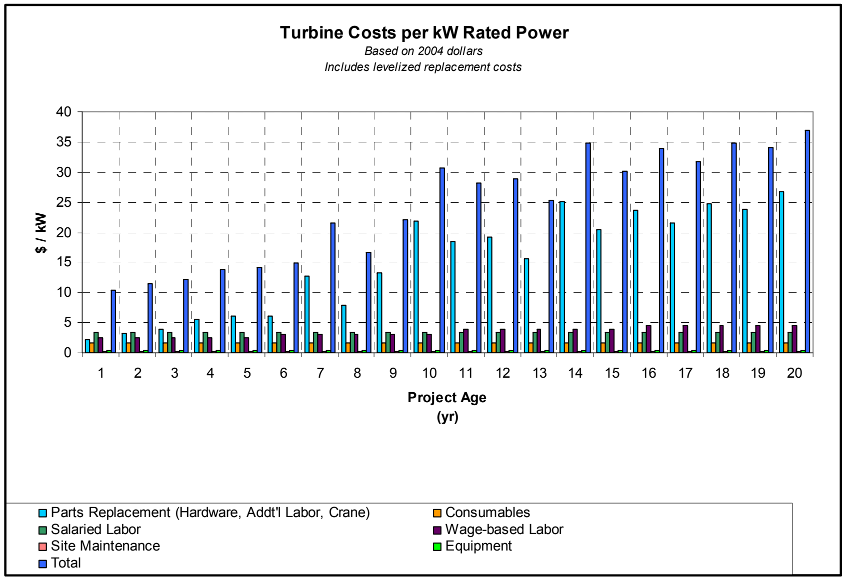
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	2.2	3.3	3.9	5.6	6.0	6.1	12.8	7.9	13.3	21.9	18.5	19.2	15.7	25.1	20.5	23.8	21.5	24.7	23.8	26.7	4.2	12.4	19.8	24.1	15.13
Consumables	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.57
Salaried Labor	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.49
Wage-based Labor	2.5	2.5	2.5	2.5	2.5	3.1	3.1	3.1	3.1	3.1	3.9	3.9	3.9	3.9	3.9	4.5	4.5	4.5	4.5	4.5	2.5	3.1	3.9	4.5	3.51
Site Maintenance	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.24
Equipment	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.40
Total	10.5	11.5	12.1	13.8	14.3	14.8	21.5	16.7	22.1	30.7	28.1	28.8	25.3	34.8	30.1	33.9	31.7	34.9	34.0	36.9	12.4	21.2	29.4	34.3	24.33

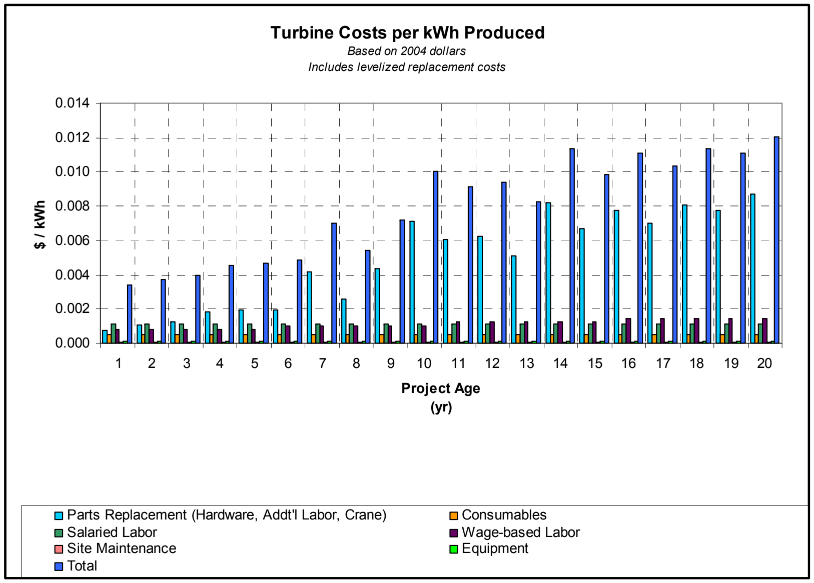
O&M $ /kWh

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware	0.001	0.001	0.001	0.002	0.002	0.002	0.004	0.003	0.004	0.007	0.006	0.006	0.005	0.008	0.007	0.008	0.007	0.008	0.008	0.009	0.00	0.00	0.01	0.01	0.00
Consumables	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Salaried Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Wage-based Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Site Maintenance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Equipment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Total	0.003	0.004	0.004	0.005	0.005	0.005	0.007	0.005	0.007	0.010	0.009	0.009	0.008	0.011	0.010	0.011	0.010	0.011	0.011	0.012	0.00	0.01	0.01	0.01	0.01


Annual Project Costs
Based on 2004 dollars
Includes levelized replacement costs
$ x 1000 / yr
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine O&M Costs
Based on 2004 dollars
Includes levelized replacement costs
$ / turbine / yr
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kW Rated Power
Based on 2004 dollars
Includes levelized replacement costs
$ / kW
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kWh Produced
Based on 2004 dollars
Includes levelized replacement costs
$ / kWh
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total

2000 kW model Results

Table 1. Wind Farm Operations

Capacity Factor (%)	35
Number of Turbines	30
Energy Sales Price ($/kw-hr.)	0.055
Power Generated (MW)	60

Table 2. Turbine Characteristics

Rating	2000
Power Conversion	Variable Speed
Pitch Control	Electric
Hub Height	80

Notes:

Description:	*2000 kw, variable speed, electric pitch, 80m tower*

Table 3. Staffing Levels and Costs

	Salary ($/year) Wage ($/hr)	*Burden (%)*	*Total*	# of Staff years 1-5	6-10	11-15	16-20	Staffing Costs ($/Year) years 1-5	6-10	11-15	16-20
Site Manager Salary	85,000	35	$ 114,750	1	1	1	1	114,750	114,750	114,750	114,750
Admin. Asst. Salary	35,000	35	$ 47,250	2	2	2	2	94,500	94,500	94,500	94,500
Sr. Tech Wage	18.00	35	$ 24.30	1	1	1	2	50,544	50,544	50,544	101,088
Jr. Tech Wage	12.00	35	$ 16.20	2	3	4	4	67,392	101,088	134,784	134,784
Totals								327,186	360,882	394,578	445,122

Table 4. Annual Turbine Consumables

Item	*User Values $/turbine*	*Default Values $/turbine*
Gear oil filter	267	267
Hydraulic filter	100	100
Offline-filter	100	100
Hydraulic oil replenish	20	20
Gear oil change (mineral)	377	377
Yaw gear grease	160	160
Bearing grease	120	120
Oil Testing	120	120
Electricity	1,752	1,752
Total	**3,015**	**3,015**

Table 5. Crane Cost (+Mobilization)

Item	**User** *$/event*	**Default** *$/event*
Blade--struct. repair	33,000	33,000
Blade--nonstruct. repai	33,000	33,000
Gearbox--gear & brgs	69,000	69,000
Gearbox--brgs, all	69,000	69,000
Gearbox--high speed c	69,000	69,000
Generator--rot. & brgs	48,000	48,000
Generator--brgs only	48,000	48,000
Main Bearing	69,000	69,000
Pitch Bearing	33,000	33,000
Yaw Bearing	69,000	69,000

Table 6. Site Equipment, Supplies & Maintenance

Annual Costs ($)

User	*Default*
$2,500	2,500
$5,000	5,000
$8,000	8,000
$2,500	2,500
$6,000	6,000
Total Equipment	**24,000**
$5,000	5,000
$4,100	4,100
$2,500	2,500
$1,700	1,700
$800	800
Total Maintenance	**14,100**

Table 7. Turbine Parts List

Part Identification		Constant Failure Rate		Weibull Failure Rate			Repair/Replacement Costs				
System	Component	Failure Prediction (Constant Rate or Weibull Curve)	Failures per 100 original parts by Year 20	Alpha	Beta	Mean Life (50% failures)	qty per turbine	Cost	Addt'l Labor to Repair / Replace (hr)	Crane?	Parts in Project
Rotor	Blade--struct. repair	**Constant Rate**	5				3	70650	43	**TRUE**	90
	Blade--nonstruct. repair	**Constant Rate**	100				3	7065	76	**TRUE**	90
	Pitch cylinder & linkage	Weibull Curve		10	3.5	9.0	0	2130	14	FALSE	
	Pitch bearing	Weibull Curve	5				3	23700	63	**TRUE**	90
	Pump & Hydraulics	Weibull Curve		12	3.5	10.8	0	3780	8	FALSE	
	Pitch position xdcr	Weibull Curve		12	2.0	10.0	0	1000	4	FALSE	
	Pitch motor	Weibull Curve		15	1.1	10.7	3	5333	4	FALSE	90
	Pitch gear	Weibull Curve		12	3.5	10.8	3	2707	10	FALSE	90
	Pitch drive	Weibull Curve		15	2.0	12.5	3	5600	4	FALSE	90
Drivetrain	Main bearing	**Constant Rate**	5				1	21000	134	**TRUE**	30
	High-speed coupling	Weibull Curve		25	3.5	22.5	1	5455	12	FALSE	30
Gearbox and Lube	Gearbox--gear & brgs	**Constant Rate**	5				1	216020	104	**TRUE**	30
	Gearbox--brgs, all	Weibull Curve		20	3.5	18.0	1	123440	104	**TRUE**	30
	Gearbox--high speed only	Weibull Curve		20	3.5	18.0	1	61720	37	**TRUE**	30
	Lube pumps	Weibull Curve		12	3.0	10.6	3	1600	4	FALSE	90
	Cooling Fan, Gearbox Coo	Weibull Curve		19	1.1	13.6	3	257	4	FALSE	90
Generator and Cooling	Generator--rot. & brgs	**Constant Rate**	5				1	76860	22	**TRUE**	30
	Generator--brgs only	Weibull Curve		17	3.5	15.3	2	4400	10	**TRUE**	60
	Power electronics	Weibull Curve		15	2.0	12.5	1	18000	8	FALSE	30
	Motor, generator coolant fa	Weibull Curve		19	1.1	13.6	3	257	4	FALSE	90
	Contactor, generator	Weibull Curve		20	2.0	16.7	3	3820	4	FALSE	90
Brakes & Hydraulics	Brake caliper	Weibull Curve		10	2.0	8.3	4	2250	6	FALSE	120
	Brake Pads	**Constant Rate**	10				4	200	0	FALSE	120
	Accumulator	Weibull Curve		6	3.0	5.3	1	5100	4	FALSE	30
	Hydraulic pump	Weibull Curve		12	3.0	10.6	1	1200	4	FALSE	30
	Hydraulic valve	Weibull Curve		12	3.0	10.6	5	120	2	FALSE	150
Yaw System	Yaw gear (drive+motor)	**Constant Rate**	5	12	3.5	10.8	4	12481	8	FALSE	120
	Yaw caliper	Weibull Curve		10	2.0	8.3	4	250	8	FALSE	120
	Yaw sliding pads	Weibull Curve		10	3.5	9.0	8	400	8	FALSE	240
	Yaw bearing	Weibull Curve	0				1	9863	134	**TRUE**	30
Control System	Control board, Top	Weibull Curve		15	2.0	12.5	1	6300	0	FALSE	30
	Control board, Main	Weibull Curve		15	2.0	12.5	1	8100	0	FALSE	30
	Control Module	Weibull Curve		15	2.0	12.5	2	1620	0	FALSE	60
	Sensor, static	Weibull Curve		14	2.0	11.7	25	410	0	FALSE	750
	Sensor, dynamic	Weibull Curve		12	2.0	10.0	2	1200	0	FALSE	60
Electrical and Grid	Main Contactor	Weibull Curve		20	2.0	16.7	1	11760	4	FALSE	30
	Main Circuit Breaker	Weibull Curve		30	2.0	25.0	1	18074	4	FALSE	30
	Soft starter	Weibull Curve		30	2.0	25.0	0	6783	8	FALSE	
Misc. (All others)	Miscellaneous Parts	**Constant Rate**	5				1	126410	0	FALSE	30

2000 kW Results

Entry Values	
Turbine Rated Power (kW)	2000
Pitch Systmem	Electric
Rotor Speed Control	Variable Speed
Turbine Quantity	30
Total Project Power (MW)	60
Project Capacity Factor	0.35

Project Parts Cost Breakdown	
Parts	10,607,932
Crane	6,012,450
Additional Labor	426883
Total	17,047,265

Gross Project Income / yr	Gross Turbine Income / yr	Annual Production (MW-hr)
$10,117,800	$337,260	$183,960

Total Project O&M Cost ($000)

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Total
Parts Replacement (Hardware)	110	178	217	280	440	406	717	501	920	886	892	969	973	1968	1267	1039	1326	1475	1322	1297	245	686	1214	1292	17183
Consumables	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	1809
Salaried Labor	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	4185
Wage-based Labor	118	118	118	118	118	152	152	152	152	152	185	185	185	185	185	236	236	236	236	236	118	152	185	236	3454
Site Maintenance	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	282
Equipment	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	480
Total	566	633	673	736	895	896	1207	991	1409	1375	1416	1492	1496	2491	1790	1613	1900	2048	1896	1870	701	1176	1737	1865	27393

O&M $ /Turbine

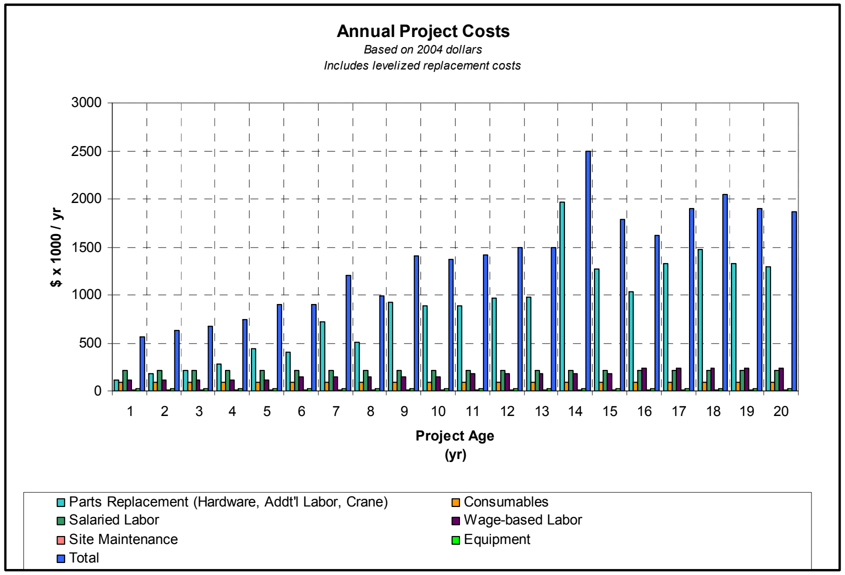
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware)	3667	5923	7228	9341	14655	13547	23910	16714	30664	29520	29748	32303	32425	65597	42223	34639	44211	49152	44062	43224	8163	22871	40459	43058	28638
Consumables	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015	3015
Salaried Labor	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975	6975
Wage-based Labor	3931	3931	3931	3931	3931	5054	5054	5054	5054	5054	6178	6178	6178	6178	6178	7862	7862	7862	7862	7862	3931	5054	6178	7862	5756
Site Maintenance	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470
Equipment	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
Total	18858	21114	22419	24532	29846	29862	40224	33029	46979	45835	47186	49741	49863	83035	59661	53762	63334	68275	63184	62346	23354	39186	57897	62180	45654

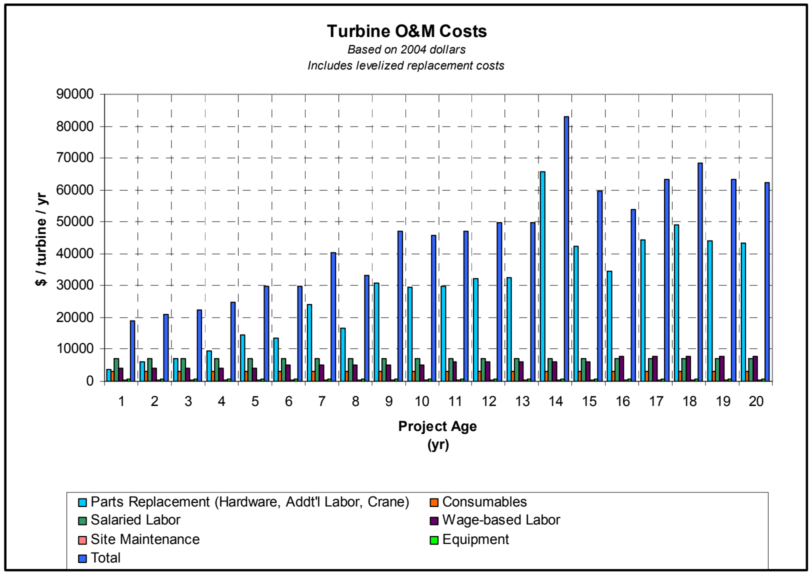
O&M $ /kW

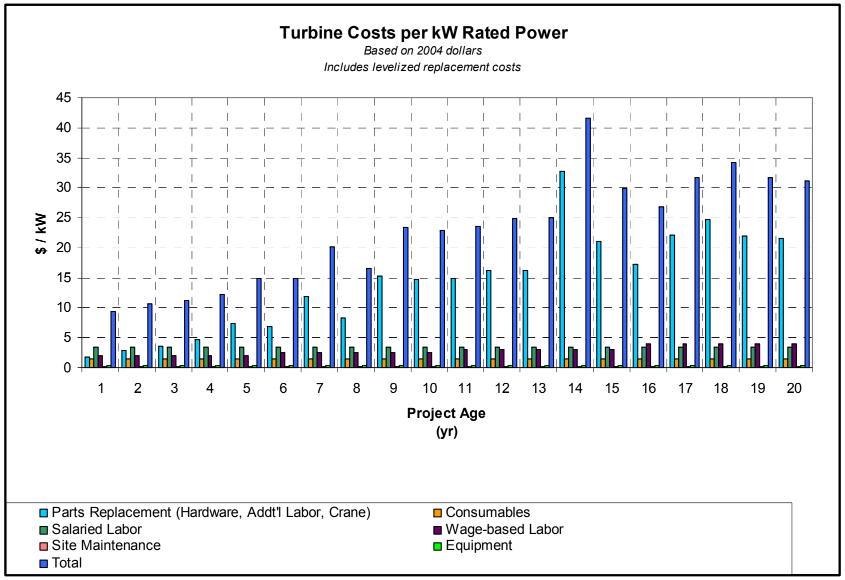
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware)	1.8	3.0	3.6	4.7	7.3	6.8	12.0	8.4	15.3	14.8	14.9	16.2	16.2	32.8	21.1	17.3	22.1	24.6	22.0	21.6	4.1	11.4	20.2	21.5	14.32
Consumables	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.51
Salaried Labor	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.49
Wage-based Labor	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	3.1	3.1	3.1	3.1	3.1	3.9	3.9	3.9	3.9	3.9	2.0	2.5	3.1	3.9	2.88
Site Maintenance	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.24
Equipment	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.40
Total	9.4	10.6	11.2	12.3	14.9	14.9	20.1	16.5	23.5	22.9	23.6	24.9	24.9	41.5	29.8	26.9	31.7	34.1	31.6	31.2	11.7	19.6	28.9	31.1	22.83

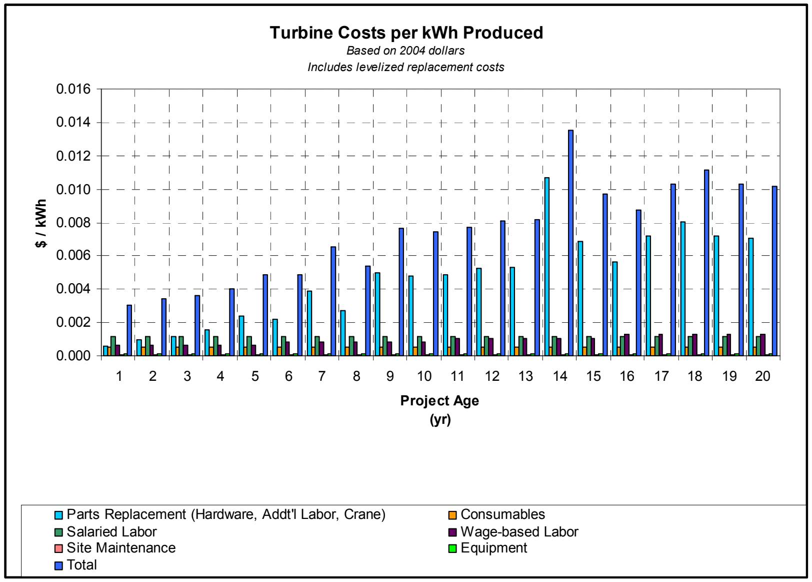
O&M $ /kWh

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average yr 1-5	Average yr 6-10	Avg yr 11-15	Avg yr 16-20	20 yr Avg
Parts Replacement (Hardware)	0.001	0.001	0.001	0.002	0.002	0.002	0.004	0.003	0.005	0.005	0.005	0.005	0.005	0.011	0.007	0.006	0.007	0.008	0.007	0.007	0.00	0.00	0.01	0.01	0.00
Consumables	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Salaried Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Wage-based Labor	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
Site Maintenance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Equipment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00
Total	0.003	0.003	0.004	0.004	0.005	0.005	0.007	0.005	0.008	0.007	0.008	0.008	0.008	0.014	0.010	0.009	0.010	0.011	0.010	0.010	0.00	0.01	0.01	0.01	0.01


Annual Project Costs
Based on 2004 dollars
Includes levelized replacement costs
$ x 1000 / yr
Project Age (yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine O&M Costs
Based on 2004 dollars
Includes levelized replacement costs
$ / turbine / yr
Project Age (yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kW Rated Power
Based on 2004 dollars
Includes levelized replacement costs
$ / kW
Project Age (yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kWh Produced
Based on 2004 dollars
Includes levelized replacement costs
$ / kWh
Project Age (yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total

2500 kW model Results

Comparison Study 2500 kW

Table 1. Wind Farm Operations

Capacity Factor (%)	35
Number of Turbines	24
Energy Sales Price ($/kw-hr.)	0.055
Power Generated (MW)	60

Notes:

Description:	*2500 kw, variable speed, electric pitch, 80m tower*

Table 2. Turbine Characteristics

Rating	2500
Power Conversion	Variable Speed
Pitch Control	Electric
Hub Height	80

Table 3. Staffing Levels and Costs

	Salary ($/year) Wage ($/hr)	*Burden (%)*	*Total*	# of Staff years 1-5	6-10	11-15	16-20	*Staffing Costs ($/Year)* years 1-5	6-10	11-15	16-20
Site Manager Salary	85,000	35	$ 114,750	1	1	1	1	114,750	114,750	114,750	114,750
Admin. Asst. Salary	35,000	35	$ 47,250	2	2	2	2	94,500	94,500	94,500	94,500
Sr. Tech Wage	18.00	35	$ 24.30	1	1	1	1	50,544	50,544	50,544	50,544
Jr. Tech Wage	12.00	35	$ 16.20	2	2	3	4	67,392	67,392	101,088	134,784
Totals								327,186	327,186	360,882	394,578

Table 4. Annual Turbine Consumables

Item	*User Values $/turbine*	*Default Values $/turbine*
Gear oil filter	333	333
Hydraulic filter	100	100
Offline-filter	100	100
Hydraulic oil replenish	20	20
Gear oil change (mineral)	469	469
Yaw gear grease	200	200
Bearing grease	150	150
Oil Testing	120	120
Electricity	2,190	2,190
Total	**3,683**	**3,683**

Table 5. Crane Cost (+Mobilization)

Item	**User** *$/event*	**Default** *$/event*
Blade--struct. repair	39,000	39,000
Blade--nonstruct. repai	39,000	39,000
Gearbox--gear & brgs	84,000	84,000
Gearbox--brgs, all	84,000	84,000
Gearbox--high speed c	84,000	84,000
Generator--rot. & brgs	60,000	60,000
Generator--brgs only	60,000	60,000
Main Bearing	84,000	84,000
Pitch Bearing	39,000	39,000
Yaw Bearing	84,000	84,000

Table 6. Site Equipment, Supplies & Maintenance

Annual Costs ($)

	User		*Default*
	$2,500	2,500	2,500
	$5,000	5,000	5,000
	$8,000	8,000	8,000
	$2,500	2,500	2,500
	$6,000	6,000	7,400
Total Equipment		**24,000**	25,400
	$5,000	5,000	8,100
	$4,100	4,100	6,700
	$2,500	2,500	4,000
	$1,700	1,700	2,700
	$800	800	1,300
Total Maintenance		**14,100**	22,800

Table 7. Turbine Parts List

Part Identification		Constant Failure Rate		Weibull Failure Rate			Repair/Replacement Costs				
System	Component	Failure Prediction (Constant Rate or Weibull Curve)	Failures per 100 original parts by Year 20	Alpha	Beta	Mean Life (50% failures)	qty per turbine	Cost	Addt'l Labor to Repair / Replace (hr)	Crane?	MTTR (days)
Rotor	Blade--struct. repair	**Constant Rate**	5				3	89150	49	**TRUE**	3
	Blade--nonstruct. repair	**Constant Rate**	100				3	8915	82	**TRUE**	3
	Pitch cylinder & linkage	Weibull Curve		10	3.5	9.0	0	2400	17	FALSE	0
	Pitch bearing	Weibull Curve	5				3	30700	69	**TRUE**	3
	Pump & Hydraulics	Weibull Curve		12	3.5	10.8	0	3780	8	FALSE	0
	Pitch position xdcr	Weibull Curve		12	2.0	10.0	0	1000	4	FALSE	0
	Pitch motor	Weibull Curve		15	1.1	10.7	3	6667	4	FALSE	3
	Pitch gear	Weibull Curve		12	3.5	10.8	3	3383	11	FALSE	3
	Pitch drive	Weibull Curve		15	2.0	12.5	3	7000	4	FALSE	3
Drivetrain	Main bearing	**Constant Rate**	5				1	29800	147	**TRUE**	1
	High-speed coupling	Weibull Curve		25	3.5	22.5	1	6818	12	FALSE	1
Gearbox and Lube	Gearbox--gear & brgs	**Constant Rate**	5				1	283850	117	**TRUE**	1
	Gearbox--brgs, all	Weibull Curve		20	3.5	18.0	1	162200	117	**TRUE**	1
	Gearbox--high speed only	Weibull Curve		20	3.5	18.0	1	81100	46	**TRUE**	1
	Lube pumps	Weibull Curve		12	3.0	10.6	3	1900	4	FALSE	3
	Cooling Fan, Gearbox Coo	Weibull Curve		19	1.1	13.6	3	257	4	FALSE	1
Generator and Cooling	Generator--rot. & brgs	**Constant Rate**	5				1	100870	24	**TRUE**	1
	Generator--brgs only	Weibull Curve		17	3.5	15.3	2	5500	10	**TRUE**	2
	Power electronics	Weibull Curve		15	2.0	12.5	1	18000	8	FALSE	1
	Motor, generator coolant fa	Weibull Curve		19	1.1	13.6	3	257	4	FALSE	1
	Contactor, generator	Weibull Curve		20	2.0	16.7	3	5010	4	FALSE	3
Brakes & Hydraulics	Brake caliper	Weibull Curve		10	2.0	8.3	4	2445	6	FALSE	2
	Brake Pads	**Constant Rate**	10				4	200	0	FALSE	2
	Accumulator	Weibull Curve		6	3.0	5.3	1	7700	4	FALSE	1
	Hydraulic pump	Weibull Curve		12	3.0	10.6	1	1200	4	FALSE	1
	Hydraulic valve	Weibull Curve		12	3.0	10.6	5	120	2	FALSE	3
Yaw System	Yaw gear (drive+motor)	**Constant Rate**	5	12	3.5	10.8	4	15603	8	FALSE	2
	Yaw caliper	Weibull Curve		10	2.0	8.3	4	250	8	FALSE	2
	Yaw sliding pads	Weibull Curve		10	3.5	9.0	8	400	8	FALSE	4
	Yaw bearing	Weibull Curve	0				1	13083	147	**TRUE**	1
Control System	Control board, Top	Weibull Curve		15	2.0	12.5	1	7850	0	FALSE	1
	Control board, Main	Weibull Curve		15	2.0	12.5	1	10200	0	FALSE	1
	Control Module	Weibull Curve		15	2.0	12.5	2	2040	0	FALSE	4
	Sensor, static	Weibull Curve		14	2.0	11.7	25	520	0	FALSE	7
	Sensor, dynamic	Weibull Curve		12	2.0	10.0	2	1200	0	FALSE	4
Electrical and Grid	Main Contactor	Weibull Curve		20	2.0	16.7	1	15540	4	FALSE	1
	Main Circuit Breaker	Weibull Curve		30	2.0	25.0	1	31920	4	FALSE	1
	Soft starter	Weibull Curve		30	2.0	25.0	0	8190	8	FALSE	0
Misc. (All others)	Miscellaneous Parts	**Constant Rate**	5				1	158010	0	FALSE	1

2500 kW Results

Entry Values	
Turbine Rated Power (kW)	2500
Pitch Systmem	Electric
Rotor Speed Control	/ariable Speed
Turbine Quantity	24
Total Project Power (MW)	60
Project Capacity Factor	0.35

Project Parts Cost Breakdown	
Parts	10,569,218
Crane	5,893,350
Additional Labor	360004
Total	16,822,571

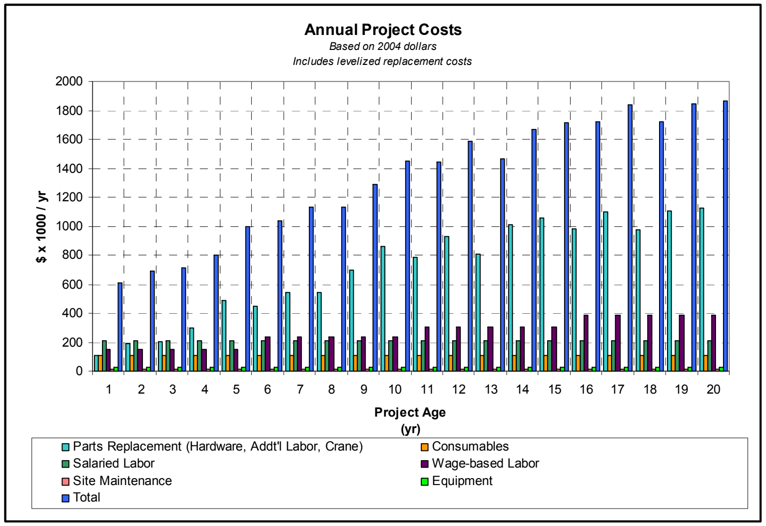
Gross Project Income / yr	Gross Turbine Income / yr	Annual Production (MW-hr)
########	$421,575	183,960

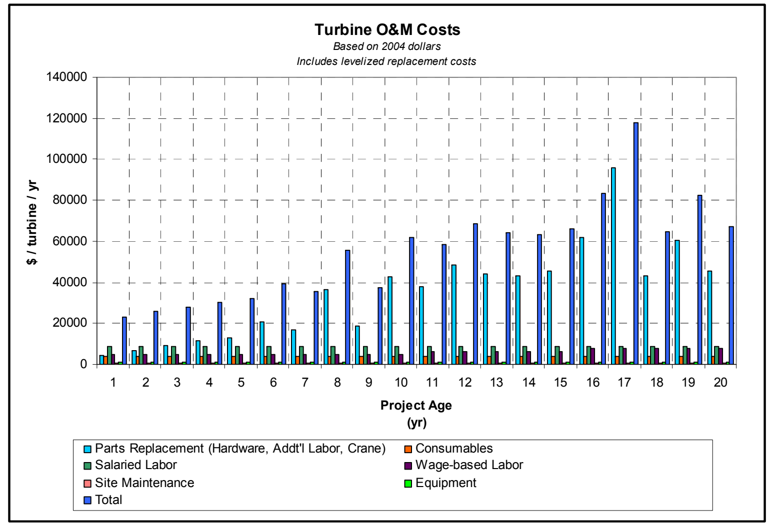
Total Project $000 /year																								
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average y	Average y	Avg yr 11	Avg yr 16-
Parts Replacement (Hardware	99	166	219	271	314	490	403	877	448	1027	913	1159	1053	1037	1097	1486	2307	1032	1455	1089	214	649	1052	1474
Consumables	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88
Salaried Labor	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209	209
Wage-based Labor	118	118	118	118	118	118	118	118	118	118	152	152	152	152	152	185	185	185	185	185	118	118	152	185
Site Maintenance	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Equipment	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Total	552	620	672	725	768	944	857	1330	902	1481	1400	1646	1541	1524	1584	2007	2828	1553	1976	1610	667	1103	1539	1995

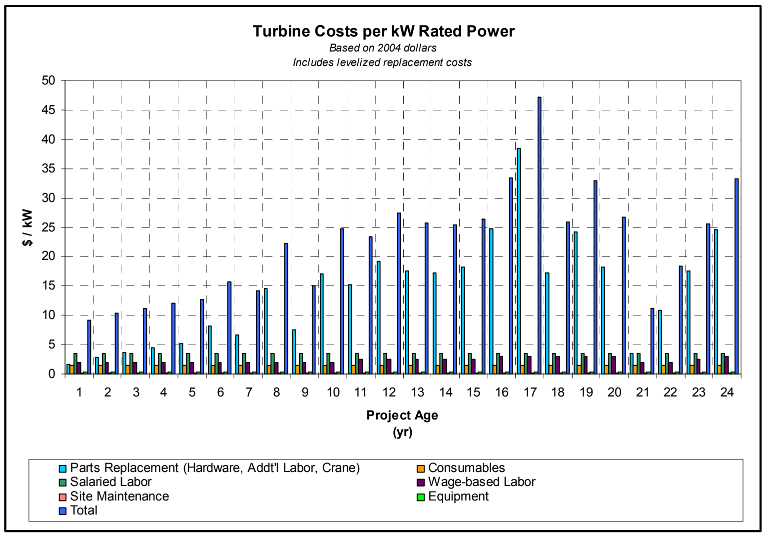
$ /Turbine /year																								
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average y	Average y	Avg yr 11	Avg yr 16-
Parts Replacement (Hardware	4113	6917	9113	11304	13078	20427	16803	36526	18678	42792	38034	48283	43884	43188	45697	61900	96119	43014	60612	45368	8905	27045	43817	61403
Consumables	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683	3683
Salaried Labor	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719	8719
Wage-based Labor	4914	4914	4914	4914	4914	4914	4914	4914	4914	4914	6318	6318	6318	6318	6318	7722	7722	7722	7722	7722	4914	4914	6318	7722
Site Maintenance	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588
Equipment	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Total	23016	25820	28016	30207	31981	39330	35706	55429	37581	61695	58340	68589	64191	63495	66003	83611	117830	64725	82323	67079	27808	45948	64124	83113

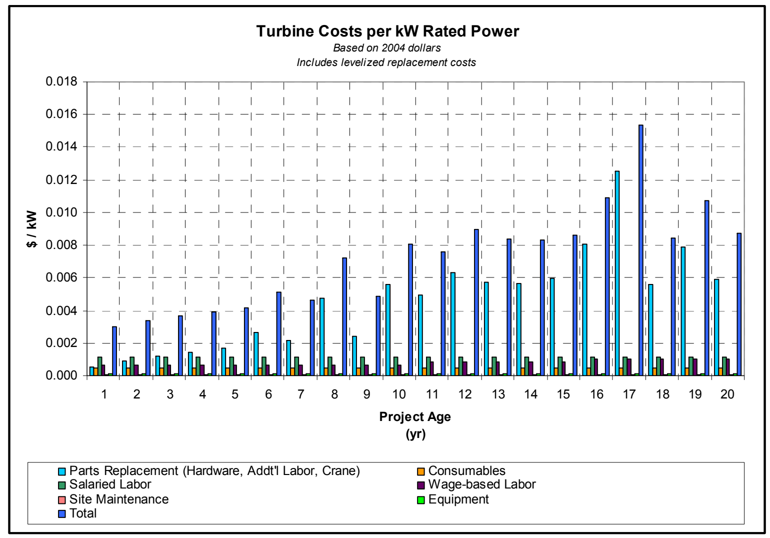
$ /kW/ year																								
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average y	Average y	Avg yr 11-	Avg yr 16-
Parts Replacement (Hardware	1.6	2.8	3.6	4.5	5.2	8.2	6.7	14.6	7.5	17.1	15.2	19.3	17.6	17.3	18.3	24.8	38.4	17.2	24.2	18.1	3.6	10.8	17.5	24.6
Consumables	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Salaried Labor	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Wage-based Labor	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	3.1	3.1	3.1	3.1	3.1	2.0	2.0	2.5	3.1
Site Maintenance	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Equipment	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	9.2	10.3	11.2	12.1	12.8	15.7	14.3	22.2	15.0	24.7	23.3	27.4	25.7	25.4	26.4	33.4	47.1	25.9	32.9	26.8	11.1	18.4	25.6	33.2

$ /kW-hr																								
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average y	Average y	Avg yr 11-	Avg yr 16-
Parts Replacement (Hardware	0.0005	0.0009	0.0012	0.0015	0.0017	0.0027	0.0022	0.0048	0.0024	0.0056	0.0050	0.0063	0.0057	0.0056	0.0060	0.0081	0.0125	0.0056	0.0079	0.0059	0.0012	0.0035	0.0057	0.0080
Consumables	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Salaried Labor	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011
Wage-based Labor	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0008	0.0008	0.0008	0.0008	0.0008	0.0010	0.0010	0.0010	0.0010	0.0010	0.0006	0.0006	0.0008	0.0010
Site Maintenance	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Equipment	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Total	0.0030	0.0034	0.0037	0.0039	0.0042	0.0051	0.0047	0.0072	0.0049	0.0080	0.0076	0.0089	0.0084	0.0083	0.0086	0.0109	0.0154	0.0084	0.0107	0.0088	0.0036	0.0060	0.0084	0.0108


Annual Project Costs
Based on 2004 dollars
Includes levelized replacement costs
$ x 1000 / yr
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine O&M Costs
Based on 2004 dollars
Includes levelized replacement costs
$ / turbine / yr
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kW Rated Power
Based on 2004 dollars
Includes levelized replacement costs
$ / kW
Project Age
(yr)
Parts Replacement (Hardware, Addt'l Labor, Crane)
Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total


Turbine Costs per kW Rated Power
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Includes levelized replacement costs
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Project Age
(yr)
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Consumables
Salaried Labor
Wage-based Labor
Site Maintenance
Equipment
Total

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The report describes the operatons and maintenance cost model developed by Global Energy Concepts under contract to NREL to estimate the O&M costs for commercial wind turbine generator facilities.

15. SUBJECT TERMS
wind energy generation; wind turbine; economic model; wind energy

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