APPENDIX B

EIA Task Order No. DE-DT0000804, Subtask 3

The Cost and Performance of Distributed Wind Turbines, 2010-35

Final Report

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Prepared for:

Office of Integrated Analysis & Forecasting
U.S. Energy Information Administration

Prepared by:

ICF International

Contact:

Robert Kwartin
T: (703) 934-3586
E: RKwartin@icfi.com

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Executive Summary

This report and its accompanying data tables provide cost and performance projections for distributed wind turbines in the 1-100 kW nominal size range over the 2010-35 period. These factors were developed by compiling manufacturer-provided cost and performance of popular present-day turbines in this size range; adjusting these 2009 data to reflect independent test results and to conform to new data definitions that will apply in 2010 and beyond; and then developing cost and performance trajectories for the forecast period. These trajectories are based on interviews with market participants, particularly manufacturers, distributed wind project developers, and researchers.

Projections were developed for both a reference case and an advanced case. The advanced case is distinguished from the reference case by an assumption of much higher private sector research and development investment, resulting in more rapid and more substantial improvements in cost and performance over the projection period.

Specific parameters include:

Performance: Turbine productivity measured in kWh generated per year is projected to increase by 28% in the base case and 36% in the advanced case over the forecast horizon compared with present-day turbine productivity.

Cost: Distributed wind installed costs, in constant dollars, are projected to fall by 20% in the base case and 24% in the advanced case through 2035.

Economic Viability: The combination of improving performance and falling cost is projected to yield a 37% and 44% reduction in installed cost per annual kWh produced in the base case and the advanced case respectively over the 2010-35 period.

Operation and Maintenance (O&M) Expenses: O&M expenses are projected to fall by 10% in the base case and by 12% in the advanced case by 2035 compared with current-day costs.

Availability: Turbine availability was assumed to be 98% under both scenarios.

Equipment Life: Turbines were assumed to have a 25-year lifetime under both scenarios.

Introduction

The purpose of this paper is to provide cost and performance projections for residential and commercial scale distributed wind turbines over the period 2010-35. These projections will be used as inputs for the U.S. Energy Information Administration (EIA) National Energy Modeling System (NEMS), the principal modeling platform used by EIA to develop its *Annual Energy Outlook*. The paper will provide an overview of existing technology, briefly explain its applicability in the market, and discuss potential changes in the cost and performance of the technology over the projection period.

This paper is not intended to be an exhaustive review of distributed wind technology. Rather, it is intended to provide a conceptual framework for analyzing the projected evolution of distributed wind technologies, and to provide a credible basis for projecting cost and performance characteristics.

1. Technology Overview

This section will discuss wind technology generally, and explain why residential and commercial customers adopt wind turbines at the lower end of the available size range. The discussion will continue with a description of the factors that influence turbine energy productivity and the components of system cost.

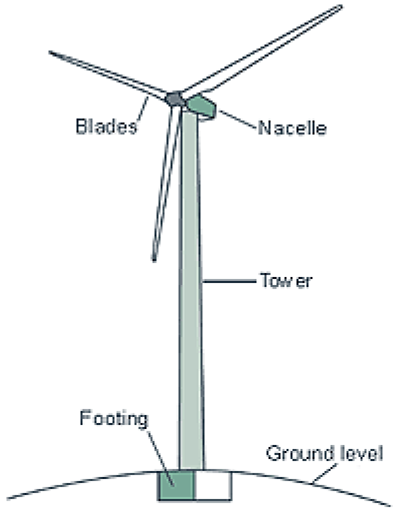

Figure 1: Main Components of a Wind Turbine[1]

Modern wind turbines capture the kinetic energy of moving air and convert it into shaft power to drive an electrical generator/alternator. The turbine is typically comprised of three basic parts: the rotor, the nacelle and the tower.

The rotor includes the turbine's blades (most often 3 in horizontal wind axis turbines) and the nose cone/hub. The nacelle contains the driveshaft, transmission[a], the unit's generator/alternator, the electronic controls to convert the generator's or alternator's electrical output to quality suitable for use, and the tail vane or yaw drive that keeps the turbine oriented to the wind, either upwind or downwind depending on the turbine's design.

Because wind speed generally increases and turbulence decreases with height, a tower helps the system increase its energy production and reduces turbulence-induced mechanical stresses, thus enhancing its economic benefit.

The ability of a turbine to produce energy from the wind fundamentally depends on the wind resource and the swept area of the turbine. Simplifying somewhat, the power output of a turbine is proportional to the cube of the wind velocity and the square of the blade length. A doubling of the wind speed thus yields an eight-fold increase in wind power while a doubling of a turbine's blade length yields a four-fold increase in energy capture (all other things kept constant).

Larger turbines with longer blades not only produce more energy for a given wind resource, they are also more capital cost-effective as well, as a result of inherent

[a] Many small turbines are direct drive. Larger turbines more often use gearboxes to step up the rotor's rotational speed to a rotational speed suitable for the generator/alternator.

economies of scale as well as inefficiencies in the market for smaller turbines. As shown in Table 5, the installed cost/kW for a small turbine is twice that for a mid-scale turbine and can be several times as expensive as that for a utility-scale turbine.

While these factors argue for choosing the windiest sites and installing the largest turbines on the highest towers that are cost-effective for the site – an argument understood by wind farm developers – residential and commercial site hosts cannot follow this logic to its conclusion. It is a rare home or business owner that is going to move their establishment simply to take advantage of a windier site. And several practical constraints prevent home and business owners from using the giant turbines typically found in utility-scale wind farms. Neighbors might object to the presence of a turbine hundreds of feet tall because of safety, noise and visual concerns. The turbine's capital costs are an additional consideration: even if a site host has the space for a giant turbine, the multi-million dollar capital cost can be difficult to finance for someone not in the wind industry. As a result of these constraints, most distributed wind turbine installations are sized roughly equivalent to the site host's electrical load and use turbines much smaller than those found in current-day wind farms. This analysis therefore assumes that residential customers will install turbines with nominal capacity ratings of 1-9 kW, while commercial customers will install turbines with nominal capacity ratings of 10-100 kW.

2. Market Overview

Distributed wind technology is used to power homes, small businesses, farms and ranches, schools and colleges, county and state facilities, and many other site hosts. Buyers are motivated by a variety of factors, typically a blend of the following:

- a distributed wind turbine may simply be a good investment;
- buyers may be seeking to moderate the volatility in the prices they pay for electricity;
- buyers may want to reduce their environmental impact by generating electricity without fossil fuel combustion;
- some buyers may be motivated by economic development concerns: a distributed wind turbine creates employment during installation and for ongoing operation, and onsite electricity generation can keep funds in the community; and
- particularly for public sector and educational institutions, there is a corollary goal of demonstrating a new technology and educating citizens and students about renewable energy-generation possibilities.

Whatever the balance between these motivations, more turbines will be purchased as project economics improve; few buyers can afford to ignore cost and economic return entirely, no matter how strongly they might otherwise be motivated.[b] Project economics are discussed in greater detail below.

The small wind market grew rapidly in the U.S. in 2008. The American Wind Energy Association's survey[2] indicates that over 10,000 small (100 kW and smaller) turbines were sold in the U.S. in 2008 with an aggregate nameplate capacity of 17.3 MW. This represented an increase of 14% in unit sales and 78% in nameplate capacity sales compared with 2007. The distribution of sales by size is shown in Table 1 and the growth in sales is shown in Figure 2 below:

Table 1: The U.S. Distributed Wind Market[c]

	0-0.9 kW	1-10 kW	11-20 kW	21-100 kW	Total
Units Sold	6,706	3,521	72	87	10,386
Capacity (kW)	2,784	7,599	1,331	5,660	17,374

[b] The author is not aware of public-domain literature providing a rigorous analysis of buyer motivation for installing distributed wind turbines. (Informal pre-purchase surveys have been conducted by *Home Power* magazine, for example, and other informal surveys have assessed barriers to purchase.) Anecdotally, it is clear that many buyers are motivated by non-economic factors, but the extent of this motivation and its relative importance in different buying segments is not clear. Such a study would increase the realism of market penetration studies by public and private analysts.

[c] The majority of turbines with nameplate capacity of 1 kW and below are purchased for off-grid applications, such as powering remote loads, off-grid cabins, boats, etc. AWEA estimates that 7,402 turbines with a nameplate capacity of 3,764 kW were sold for off-grid uses in 2008. These applications are not represented in NEMS and are not further treated in this paper.

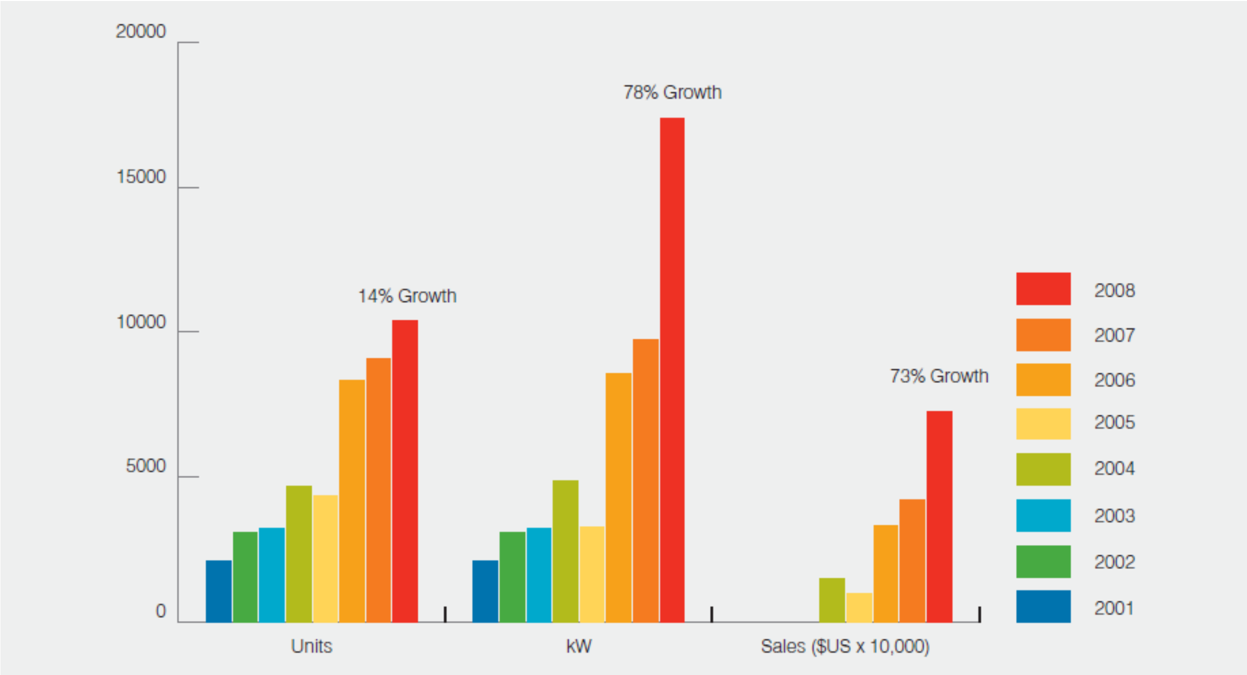

Figure 2: Growth of the Small Wind Market in the U.S.[3]

3. Potential Market Size

The potential market for distributed wind is constrained by technical and economic factors.

3.1 Technical Factors

A proposed distributed wind project can be impaired by a number of different technical considerations. The most important is the availability of wind. A site with poor wind resources cannot support an economically viable wind project. Figure 2 below provides a coarse-scale representation of the country's wind resources at a 50-meter hub height; the map displays Wind Power Classes, which are based on wind power density (Watts of wind power per square meter of rotor cross section).

Although it is not an ironclad rule, in general, if a site has a wind resource below Wind Power Class 3, it is unlikely to be economically successful. Almost 70% of the land surface in the Lower 48 states is in Wind Power Classes 1 and 2.[4] At the lower hub heights used for the small to mid-scale turbines evaluated in this paper, the percentage of low-wind surface area is even higher.

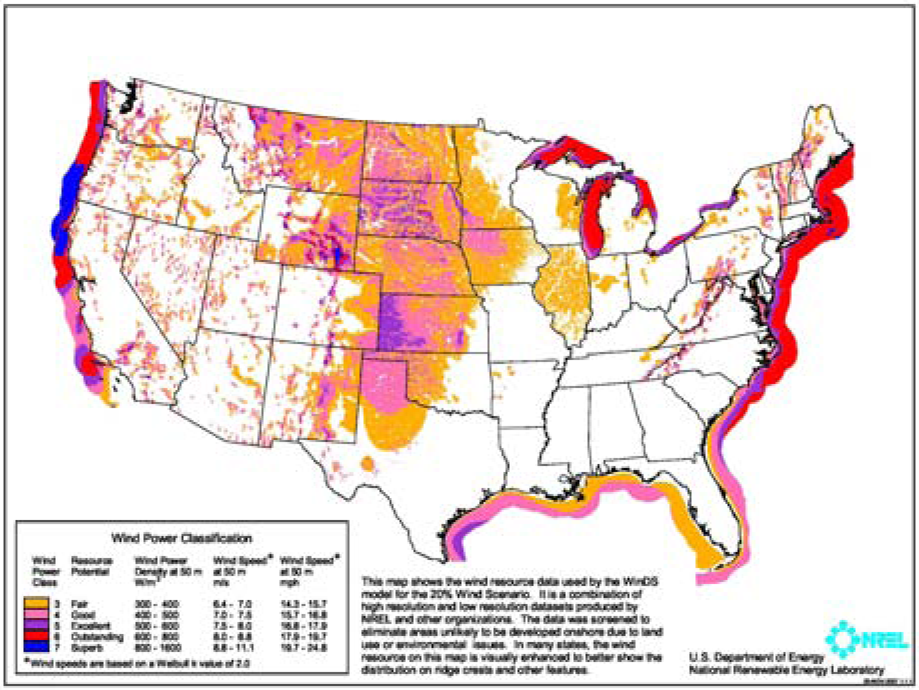

Figure 3: National Wind Resource Map

Land availability and usability is the second most important technical factor. The land parcel on which the turbine will be sited needs to be of sufficient size to satisfy any local zoning codes related to set-back as well as safety, noise and visual considerations. In addition, the parcel must have sufficient room so that the turbine will not be in close proximity to trees, structures or other features that can slow the wind or create turbulence. Smaller residential turbines mounted on towers of appropriate height typically require a parcel of half an acre or a full acre[5]. Northern Power Systems recommends 500 feet of clearance around one of its 100 kW turbines, equivalent to an 18 acre parcel.[6] Thus, it is difficult to implement distributed wind turbines in cities and heavily developed suburbs[d].

Several other technical issues constrain the implementation of distributed wind: steep terrain; high elevations; zoning restrictions on tower heights; availability of 3 phase power (generally for machines > 30 kW), concerns about bird and bat kills; etc.

[d] Vertical axis wind turbines (VAWT) have some potential to fit into smaller land parcels, as they can be installed on lower towers or even mounted on buildings, and thus require less set-back. Doing so, however, reduces the available wind resource and increases mechanical stress arising from turbulence. VAWTs have generally suffered from lower energy productivity compared with horizontal axis turbines and have struggled to demonstrate their commercial viability.

3.2 Economic Factors - Benefits

The financial analysis of a wind project includes the following factors:

- **Revenue from electricity generation**. In most cases, the majority of the "revenue" from a distributed wind turbine's electricity generation is actually the displacement of electric power deliveries by the electric utility. This displacement of electricity sales at relatively high retail rates is usually the largest single revenue source for a distributed wind turbine.[e] Any excess electricity above the site's consumption can be sold the local electric utility, but the value of these sales varies dramatically. At a minimum, utilities are obliged to pay at least some proxy for wholesale electricity prices for electricity purchased from a customer/generator. In many states, excess generation of electricity above the site's consumption can be sold back to the distribution utility at the full retail rate and excess generation from one month may be carried over to net against electricity purchases in subsequent months, often for up to a year.[7]
- **Benefits from policy support**. A variety of public policies provide additional benefits to distributed wind project owners:
    - **Federal tax benefits**. At the Federal level, tax benefits are available to distributed wind turbine owners. The most important is the recently-enhanced Investment Tax Credit (ITC). This credit is valued at 30% of the project's installed cost, without any upper limit on the credit amount, and is available through December 31, 2016. Under Section 1603 of the American Recovery and Reinvestment Act, this tax credit can also be converted into an outright cash grant from the Treasury, which is particularly favorable for taxable entities that do not anticipate sufficient taxable income to take full advantage of the ITC and for entities that prefer the certainty of a cash grant in the near term to a tax credit taken during one or more subsequent tax years. This conversion option is available only if significant project efforts (5% of project costs) are made by December 31, 2010. Alternatively, a project may take advantage of the Production Tax Credit (PTC), worth approximately 2 cents per kWh when output is sold to an unrelated third party over a 10-year period. (For the majority of distributed wind projects, the ITC is more valuable than the PTC.) In addition, wind turbines are eligible for accelerated depreciation under the Modified Accelerated Cost Recovery System.[8]
    - **Direct spending benefits**. Federal and State agencies provide incentives for distributed wind projects through a variety of programs. For example, the U.S. Department of Agriculture's Rural Energy for America

[e] The valuation of displaced electricity requires some analysis. For residential customers with simple kWh meters, displaced electricity will be worth the full retail rate (less any fixed customer charge). For commercial/industrial customers whose tariffs include both capacity (kW) and energy (kWh) based charges, consideration needs to be given to the uncertainty as to whether the wind turbine will reliably reduce the kW-based charges, for example, by comparing the facility's load profile against the likely power production profile of the turbine. Unlike photovoltaic technology in hot climates, distributed wind generation cannot be assumed to be peak-coincident. In reality, a distributed wind turbine may not reliably avoid the peak capacity charge at all, in which case its displacement value is limited to the energy component of the tariff.

Program offers grants for feasibility studies and renewable energy installations. Many states offer direct grants for distributed wind projects or production-based incentives.

- **Renewable Energy Certificates (RECs)**. RECs can be understood to represent the positive environmental and fuel diversity attributes arising from the generation of each MWh of renewable electricity. RECs can be marketed separately from the electric commodity and are purchased by entities subject to state Renewable Portfolio Standards to satisfy their obligations under those programs ("mandatory RECs"). In addition, many electricity customers purchase RECs voluntarily to "green up" their electricity supply ("voluntary RECs"). A distributed wind project owner can choose to retain the RECs created by their project (to keep their own electricity supply "green"), or sell the RECs created by their project, or some combination of the two. REC sales can be a significant additional revenue stream for a distributed wind project.
- **Other policy support**. A variety of other policy tools are used to enhance the financial viability of distributed wind projects: government-sponsored low-interest loans, sales tax abatements, property tax abatements, state income tax credits and deductions, preferential feed-in/buy-back tariffs, etc. These policy tools evolve rapidly; refer to the Database of State Incentives for Renewables and Efficiency (DSIRE) for additional details.

3.3 Economic Factors - Costs

The most important cost component for a distributed wind project (60-80%) is the cost of the hardware: rotor, nacelle and tower. Transportation and installation costs (including labor, equipment rental, concrete, wiring, metering, interconnecting with the distribution utility, etc.) can be considerable (10-35%), particularly with taller towers, remoter sites and more difficult terrain. Pre-construction costs – feasibility analyses, project design, permitting, zoning, etc. -- may be modest for a rural residential project confronting limited zoning and permitting challenges, but run to tens of thousands of dollars for a commercial-scale project with more complex design and engineering requirements, and can account for 5-15% of initial project costs. In addition, turbine owners need to plan for annual operation and maintenance (O&M) costs, warranty expenses, as well as costs related to insurance, incremental property taxes (if any), and eventual decommissioning of the turbine when it reaches the end of its useful life.

Example capital costs for present-day distributed wind turbines are shown in Table 5; O&M costs are show in Table 7.

3.4 Market Potential - Conclusions

A recent analysis evaluated the technical and economic potential of existing mid-scale distributed wind projects in the 10-5000 kW size range[f]. The analysis found that

[f] The study evaluated individual turbines up to 1000 kW as well as small community wind projects consisting of five 1000 kW turbines.

commercial, industrial and institutional buyers motivated purely by economics would purchase over 2700 10 kW turbines, about 10,000 50 kW turbines, approximately 200 100 kW turbines, and about 3500 250 kW turbines if 2008 incentive levels were assumed to remain unchanged for 10 years. [9]

This study had some important limitations. It did not evaluate residential buyers in the 1-10 kW range. It also did not attempt to quantify market penetration driven by non-economic factors, such as the desire to reduce greenhouse gas emissions, even though anecdotal information suggests that non-economic factors are important drivers of distributed wind projects. In addition, the study was completed prior to the implementation of the uncapped 30% ITC, which can be expected to dramatically increase the number of viable projects.

This study also evaluated the impact of improving today's mid-scale distributed wind turbines. Longer blades, taller towers, greater productivity (particularly at low wind speeds), and lower costs combined to increase the potential market for 250 and 500 kW turbines by a factor of 25 or more.[10]

A second study provides market potential estimates based on technology application:

Table 2: Market Projections of Grid-Connected Domestically Installed Wind Turbines[11]

Cumulative Units Installed	Residential (1-25 kW)	Farm, Business, Industrial (10-400 kW)
2005	1,800	20
2010	6,250	1,270
2015	14,000	4,270
2020	36,500	7,395

4. Performance Objectives

Ideally, a wind turbine would extract the maximum amount of kinetic energy from the wind at the lowest possible cost. However, wind turbines, like all other goods, represent a set of compromises to satisfy multiple goals. These include:

1. **Energy productivity**: Turbines vary in their ability to extract energy from the wind, and all other things being equal, a turbine that produces more energy from a given wind resource is more valuable than a turbine that produces less. This can be achieved by using longer blades, more efficient blade design, more efficient transmission (or direct drive), a more efficient generator/alternator, better yaw control, etc. The turbine's behavior over a dynamic range is also a critical factor: turbines can be designed to start spinning at lower speeds, to produce more energy at the most frequent wind speeds, or to continue producing at higher wind speeds, but it is difficult to design a turbine that can do all three.

Because wind is variable at a given site and even more variable across many sites, no one turbine model is optimal for every site.

2. **Project Cost:** Turbines are expensive, and manufacturers seek out ways to reduce costs. This can include using less-expensive materials, improving manufacturing techniques, sourcing less-expensive components, and improving the efficiency of distribution and installation. Volume is an important determinant: many turbine models in the 1-250 kW range are produced in limited quantities, which drives up unit costs. Larger production runs give the manufacturer more leverage in negotiating with upstream suppliers, and permits more investment in production tooling.
3. **Overspeed Control:** Once the turbine is producing at its maximum output, any further increase in wind speed is essentially “wasted” from a power generation perspective and at very high speed can cause structural damage to the turbine. Turbines use a variety of methods to regulate turbine loading and rotational speed: by furling the rotor towards the tail vane (thereby reducing the rotor cross-section presented to the wind), deploying various types of blade-mounted brakes, changing the blade pitch, stalling, and/or by electrical braking.
4. **Tower Height and Cost:** In most terrains, wind speed increases with height, at least for tens of meters. Tall towers improve cost-effectiveness in most areas. Some turbines are available on tilt-up towers, while others can only be mounted on fixed towers. For fixed towers, erection costs increase as tower height increases. Taller towers also make maintenance visits more hazardous and time-consuming, driving up O&M costs.
5. **Reliability/Durability*:*** Utility-scale wind farms can afford to have on-site technicians to provide regular maintenance and repair services. A single distributed wind turbine at a home or business cannot be expected to receive the same level of attention, and therefore should be designed and built to minimize maintenance requirements. (Some level of maintenance will always be required.) Although wind turbines have few moving parts, they are subjected to significant stresses and vibration from winds that vary in speed and direction. The rotor and drivetrain is expected to spin hundreds of times per minute with blade tip speeds of over 100 mph, and this performance is expected to last for decades. To reduce maintenance costs, production degradation and downtime, the turbine should be built with well-engineered components fabricated from long-lasting materials. However, this drives up costs. Lower rotor speeds can increase longevity, but at the cost of reduced energy production.
6. **Noise:** Several design choices that increase energy productivity (longer blades, higher rotational speed, and certain overspeed controls, such as furling) increase the sound pressure produced by the turbine. This tradeoff can be particularly objectionable for distributed wind turbines as they are ordinarily sited close to homes and businesses.

NEMS “builds” distributed generation (DG) in future years based on how cost-effective the technologies are. NEMS incorporates a 30-year discounted cash flow model that assesses the internal rate of return (IRR) of various DG technologies; NEMS then uses the IRR and a learning function model to forecast the technology’s penetration in the marketplace. Other thing being equal, if a DG technology's IRR increases in a future year, it will penetrate the market further than if its IRR remains unchanged or falls.[12]

Of the key performance objectives listed above, only the turbine's cost and performance figure into the IRR calculation. Overspeed control, reliability/durability and noise are not considered. In the real world, however, these parameters are part of the turbine design process, and manufacturers make necessary compromises to ensure that turbines perform safely and reliably over the long run. The cost and performance projections presented later in this paper were developed under the assumption that manufacturers would continue to balance multiple objectives in the future as they have done in the past.

It is also important to note that NEMS only considers decisions made on economic grounds; the model does not endogenously account for turbines installed for reasons other than economics.

5. Interpreting Performance Data for Distributed Wind Technology

Distributed wind technology performance data needs to be interpreted with care. The challenge arises partly from a lack of industry standardization, partly from the highly site-specific performance of wind turbines, and partly because some manufacturers provide inaccurate or incomplete data to their buyers.

Industry standardization. Until very recently, the distributed wind industry lacked standardized terminology, test methods or product certification processes. Rated capacity, for example, is a less meaningful metric than it may seem. Manufacturers choose the wind speed at which they rate their turbines' capacity, and as noted in Table 4, the values can vary considerably. This makes it difficult to make an "apples to apples" comparison of two turbines even of the same nominal rated capacity; one may be rated based on an 11 m/s wind, for example, while another is rated at 14 m/s.

Lack of industry standardization should begin to recede as an issue in the near future. The American Wind Energy Association (AWEA) published a performance and safety standard for small wind turbines[g] in late 2009 that established specific test methods for various performance parameters, including rated capacity, annual energy production, and noise.[13] For example, the standard established that a turbine's capacity should be rated at a wind speed of 11 m/s.

In addition, 2010 will see the Small Wind Certification Council commence operations. The SWCC is an independent organization that will certify turbine testing conducted in accordance with the AWEA small wind turbine standard, provide an SWCC label to certified turbines, and provide test results on its web site.[14] The combination of standardized test methods and independent certification of testing results will make a material contribution to improving the usefulness of turbine performance data.

[g] The standard applies to turbines with swept areas of 200 square meters, or a rotor diameter of about 16m. This translates to a nominal capacity of about 65 kW.

Site-specific data. Although a turbine's rated capacity is often the first point of reference, in fact, the most important metric for a wind project is the turbine's estimated annual energy production (AEP) for the project site. This metric drives the project's potential revenue much more directly than rated capacity does. To estimate AEP, it is necessary to know the following information:

- The project's hub height;
- The wind resource distribution: how many hours per year the wind blows within specific speed ranges (bins) at the project's hub height;
- Turbulence at the project's hub height due to nearby trees, buildings and other obstructions;
- The turbine's production curve: how many kWh the turbine produces for each specific wind speed bin.
- The turbine's expected availability and losses (e.g., line losses)

For large, utility scale projects, it is typical to measure the wind resource at hub height at multiple points across the development area for at least a year-long period, and then to use sophisticated software to estimate the effects of terrain and of the turbine array itself on AEP for each turbine. Distributed wind projects in the 1-100 kW range rarely utilize such a data-intensive approach, usually only at the upper end of the range. Instead, homeowners, turbine dealers and project developers rely on a combination of coarse-scale wind maps (themselves derived from extensive modeling) and manufacturer-supplied production curve data.

It is not uncommon for this approach to result in significant mis-estimation of AEP. To start with, the typical state-level coarse-scale wind map is merely a starting point for wind estimation. Actual wind conditions within each of the map's raster cells can vary dramatically. Second, even assuming that the map provides an accurate estimate of the wind resource at a specific site, the map may be estimating wind resources at one height (e.g., a 50-meter hub height), but the turbine may be mounted at a different height (e.g., 30 meters, where wind power is substantially less). Or turbulence caused by site conditions (e.g., nearby buildings or large trees) may be ignored, although it can have a powerful effect on turbine performance.

A third factor is incorrect or incomplete information supplied by manufacturers, particularly the turbine's power curve. (See Table 3 below.) For example, one widely-used distributed wind turbine (Turbine A) has recently undergone independent testing at NREL. Comparing NREL's measured data with manufacturer literature indicates that the manufacturer overstates AEP by 71% at the AWEA reference speed of 5 m/s. The differences between NREL's measured data and manufacturer literature data were somewhat lower at higher wind speeds, falling to a 25% difference at an 8 m/s annual average wind speed for this turbine. Note, however, that the literature associated with Turbine B goes to some lengths to qualify potential turbulence factors at various wind speeds (e.g., hedges, windbreaks, buildings) and appears to have adjusted its AEP values accordingly.[15]

Table 3: Percentage Difference between Manufacturer Literature and NREL Test Data[h]

Average Annual Wind Speed	Wind Turbine A	Wind Turbine B	Wind Turbine C
4 m/s	NA	NA	46%
5 m/s	71%	-23%	26%
6 m/s	43%	-24%	9%
7 m/s	31%	NA	NA
8 m/s	25%	NA	NA

Manufacturers and dealers may also deemphasize noise considerations or fail to educate the buyer on the desirability of (or need for) a tall tower. The advent of the AWEA small wind standard and the SWCC will make it easier for buyers to obtain accurate and meaningful information, but only education will ensure that buyers get the most value from their significant investment in distributed wind.

6. Data Issues – Implications for NEMS

NEMS “builds” distributed wind turbines in Census divisions, which are then overlaid with an NREL wind map. NEMS refers to the geographical overlay of a Census division and wind map polygon as a “niche”. For each niche, NEMS estimates the distribution of wind speeds using a Weibull k of 2 and a wind shear exponent of 0.2.

The model then estimates AEP by applying a turbine’s rated capacity across a cubic power equation.

This method is vulnerable to the following sources of error:

- The wind resource map may not be appropriate for the turbine’s hub height;
- The wind speed distribution may not be appropriate in light of the topography of the niche;
- The varying altitude across the niches may not be appropriately incorporated into the computations;
- Turbulence may not be appropriately represented;
- The nominal power curve may not be appropriate for other specific turbines;
- Scaling the AEP based on ratios of rated capacity may not be appropriate in view of the inconsistency of capacity rating methods.

[h] Values represent the difference between the manufacturer’s data and NREL’s data, divided by the NREL data. Positive differences indicate that manufacturer AEP data are higher than NREL AEP data for the same average annual wind speed. Manufacturer data for Turbines B and C were not available for unit values of m/s and were interpolated from values expressed in half meters per second (e.g., 4.5 m/s, 5.5 m/s, etc.) using a simple average.

Going forward, the author recommends that EIA take the following steps to increase the realism of its modeling efforts:

1. Verify that the national wind map corresponds to the hub heights of the typical distributed wind turbine, for example 30-40 meters.
2. Consider whether to vary the Weibull k and wind shear exponent based on the land surface and altitude within the niche.
3. Altitude and turbulence factors could also be more directly represented (e.g. the decrease in air pressure at higher altitudes will decrease the energy output for a wind turbine at a lower altitude, all other things being equal).
4. As soon as it becomes available in quantity, use AWEA-standard AEP data that have been certified by the SWCC for the base year, and use these data to interpolate the AEP for other turbine sizes that have not yet been certified by SWCC.
5. Until SWCC data become available:
    a. use manufacturer-supplied AEP data for the base year, but derate these data to reflect the discrepancies described in Table 3 above.
    b. apply the adjusted AEP data to specific sites, and further modify the data to reflect local wind resources, altitude, Weibull k, and wind shear exponent.

7. Technology Baseline

Cost and dimensional data for baseline distributed wind technology are represented in Tables 4 and 5 below. The turbines chosen for this table were selected to represent a range of project capacities and are popular models within their respective size classes. Note that each turbine's rated capacity is derived from a different reference wind speed.

Table 4: Dimensional Data for Selected Distributed Wind Turbines

Manufacturer	Model	Rated Capacity (kW)	Rated Wind Speed (m/s)	Rotor Diameter (m)	Typical Tower Height (m)
Southwest Windpower	Skystream 3.7	2.4	13	3.7	26
Bergey	BWC XL-S	10	14	7	37
Entegrity	EW50	50	11.3	15	37
Northern Power Systems	Northwind 100	100	14.5	21	37

Table 5: Cost and Performance Data for Selected Distributed Wind Turbines, 2009[16]

Model	Rated Capacity (kW)	Rated Wind Speed (m/s)	Rotor Diameter (m)	Typical Tower Height (m)	Installed Cost ($)	Installed Cost/kW ($)	AEP @ 5 m/s average annual wind speed (kWh)
Skystream 3.7	2.4	13	3.7	26	$ 19,000	$ 7,917	3,600
BWC XL-S	10	14	7	37	$ 62,000	$ 6,200	13,200
EW50	50	11.3	15	37	$ 230,000	$ 4,600	72,000
Northwind 100	100	14.5	21	37	$ 435,000	$ 4,350	145,000

8. Sources for Improvement

8.1 Technological

Advances in modeling, materials science, fabrication techniques, blade design and electronics have allowed utility-scale turbines to grow steadily and to harvest the scale economies of that growth for almost 3 decades. Technological improvement has translated into lower installed cost per kW, greater energy production, and higher reliability.

However, as discussed above, it is not practical for the typical residential or business customer to enjoy these benefits by following the modern turbine's increase in size and hub height. The distributed wind turbine purchased by these customers has seen less rapid improvement, but particularly in recent years, significant improvement has been achieved. In some instances, small turbines have been earlier adopters of advanced technologies compared with larger turbines.

A utility-scale example offers the first demonstration that technological improvement is possible without an increase in size. As shown in Table 6 below, the GE 1.5 MW turbine has improved steadily in just the past seven years – without a capacity uprating – through incremental application of an improved generator and main bearing design, a better blade pitch mechanism, longer blades, and an improved gearbox. [17]

Table 6: Improvement in the GE 1.5 MW Turbine

	2002	2009
Rotor Diameter (m)	70	82.5
Capacity Factor (%)	39	52
Reliability (%)	85	98

A second example falls in the distributed wind size range. First produced in 1983, the Bergey Excel has undergone significant development over the years. The original airfoil has been succeeded by two new generations, as has the inverter, most recently in 2008. 2008 also saw the introduction of a new neodymium-based alternator. The cumulative effect of these changes is a 30% increase in energy production, a reduction in noise, and no increase in price.[18]

Distributed wind turbines still have substantial performance improvement potential; the representative of one distributed wind manufacturer believes that a 10-20% improvement in cost and productivity for this category over the next 5 year period will be "easy".[19] Improvement may be found in several areas:

- Blades and rotor: Improved blade designs, lighter-weight and stronger materials, and improved manufacturing techniques may allow for lower cut-in speeds, greater low-speed energy production, lower-noise overspeed control, and greater AEP per square meter of rotor cross-section. Current day blades are estimated to be about 32% efficient; an industry workshop set a goal of 42-45% efficiency.

- Generators: Many distributed wind turbines are now equipped with rare-earth permanent magnet generators, which are smaller, lighter, and more efficient than ferrite or wound-rotor generators.

Physical Performance Limits

A turbine cannot extract 100% of the power available in a stream of wind. If it did, the wind would stop, and so would the turbine. The upper limit in practice is 59%, known as the Betz limit after its discoverer, Albert Betz. Modern utility scale turbines extract about 50% of the wind energy at wind speeds below their rated wind speed.[a]

- Inverters: Many small distributed wind turbines use inverters optimized for photovoltaic systems. Inverters optimized for small wind turbines would have a larger voltage range, and, potentially, greater efficiency.

- Drivetrain: Most distributed wind turbines use direct drive whereby the rotor directly drives the generator, without the use of a gearbox to step up the rotational speed. Direct drive increases efficiency by eliminating gear losses, and also eliminates a frequent point of failure.

- Control electronics: At the larger end of the distributed turbine range, it may be possible to incorporate more advanced sensors and pitch controls to mitigate blade and tower loading, and thus enable the use of longer blades with greater energy capture.

8.2 Cost

Anecdotal evidence suggests that initial cost and long-term investment rate of return are the two most important factors in whether a distributed wind turbine is purchased and installed. There are several opportunities to significantly reduce the first cost of the turbine, the cost of installation, and ongoing cost of operation and maintenance:

- **Volume:** Many distributed wind turbine models have limited production volumes. As the market matures, higher volumes can drive down unit costs through more efficient operation of manufacturing plant, lower input costs, and better amortization of fixed costs. In addition, higher volumes (and revenue) can justify greater investment in more advanced tooling and manufacturing capacity. In 2008, over $160 million was invested in small wind manufacturers worldwide, with about half the funds invested in the United States.[20]

- **Greater competition:** In certain market segments, only one or a few manufacturers offer a product and have the dealer network available to support a project in a specific region. Some turbines are in short supply or only built-to-order. As more companies enter the market, customers will enjoy a greater choice of technology, shorter lead times, and a more competitive service environment.
- **Industry consolidation:** While industry diversity will benefit certain segments compared with today's baseline, other segments may benefit from some consolidation, which would allow greater scale economies in manufacturing, distribution and after-market service.
- **Outsourcing:** The U.S. is currently a leading area of distributed wind turbine manufacturing; U.S. manufacturers account for about half of global small wind sales, and about 95% of the U.S. market.[21] However, other countries, particularly China, are clearly bidding to enter the renewable energy market generally and the distributed wind market specifically. Imports from regions with lower manufacturing costs may put pressure on U.S. distributed wind turbine prices.
- **Component reduction:** Some of the performance improvements discussed above may increase costs, but others, such as eliminating the gearbox using direct drive, can serve to reduce turbine costs.
- **Tower:** Tower costs and crane rental can be a substantial fraction of total installed costs for a distributed wind turbine. Greater use of tilt-up and self-erecting towers, as well as lighter weight towers could reduce project costs.[22]
- **Operation and maintenance costs:** O&M costs could potentially be reduced through hardware and software improvements. Hardware improvements include the elimination of the gearbox, better lubrication, and more durable blade materials which are also more resistant to fouling. Software improvements include design strategies that reduce rotor and tower loading, better yaw and overspeed controls, and better monitoring technology to minimize the need for site visits and to provide early warning of emerging problems. The baseline (2010) O&M costs are shown in Table 7 below.

Table 7: Annual Operation and Maintenance Expenses[23]

Assumed Annual Expenses	Unit	Expense
Operations & Maintenance	$/kWh	$0.0100/kWh
Operations & Maintenance Contingency Fund	$/kWh	$0.0030/kWh
Insurance	$/kW	$6.70/kW
Property Tax	$/kW	$4.70/kW

Admin/Financial/Legal Management	$/kW	$0.30/kW
Warranty Expense	$/kW	$7.70/kW
Decomm. Fund Post-Warranty Expiration	$/kW	$1.00/kW
Other Expense	$/kW	$1.30/kW

9. Projection Methodology

For the purposes of the NEMS projections, it was assumed that the 2010 baseline was represented by the turbines listed in Tables 4 and 5 above. Essentially, the four turbines were assumed to become the prototypical turbines for the next 25 years. For the base year, each turbine's AEP was derated to some degree to reflect the findings shown in Table 3. The derating was not constant across turbines. Maintenance costs were taken from Table 7.

The future is represented by two scenarios: a base, or reference case; and an advanced case.

Under the base case, it is assumed that present-day policies will continue in force until their legislated expiration (if any); that present-day research and development investment flows will continue; and that the trend of technology and cost improvement will continue in the future much as it has in the recent past.

The advanced case is similar to the base case, except that it assumes a much higher level of private sector R&D investment, and thus more rapid and more extensive improvements in technology performance and more rapid and deeper reductions in cost. The advanced case does not assume any changes to the policy environment compared with the base case.[i]

For the period 2010-35, three improvement trajectories were developed:

- Cumulative AEP Improvement: This trajectory describes the increase in kWh produced by a turbine compared with its 2010 baseline.
- Cost Improvement Factor: This trajectory describes the reduction in a turbine's installed costs, in constant dollars, compared with its 2010 baseline.

[i] The implementation of the uncapped 30% ITC in February 2009 is perhaps the most important policy initiative in favor of distributed wind in several decades. This policy will only begin to have full impact in 2010 and beyond; in effect, the base case does not fully reflect this new policy. This policy could lead to larger market volumes, greater private sector investment, etc., producing a scenario more consistent with the advanced case.

- O&M Factor: This trajectory describes the reduction in annual O&M costs compared with the 2010 baseline.

Table 8: Assumptions for the Base and Advanced Cases

	Cumulative AEP Improvement Factor vs. 2010		Cost Improvement Factor vs. 2010		O&M Factor vs. 2010	
	Base	Advanced	Base	Advanced	Base	Advanced
2015	10%	12%	-8%	-10%	0.98	0.97
2020	18%	21%	-13%	-14%	0.96	0.94
2025	23%	28%	-16%	-18%	0.94	0.92
2030	26%	33%	-18%	-21%	0.92	0.90
2035	28%	36%	-20%	-24%	0.90	0.88

Other assumptions include:

- Capacity factor: As noted above, the authors recommend using AEP as the key metric of energy performance. However, the accompanying data table provides calculated capacity factors for different turbines over the projection horizon by turbine size, year and scenario.

- Equipment life: A 25 year life was assumed for both scenarios.

- Availability: We assume 98% availability in both scenarios.

- O&M Costs: Summing the values in Table 7 yields an annual O&M factor based partly on capacity ($21.70/kW-year) and partly on energy production ($0.013/kWh).

Endnotes

[1] http://www.industry.nsw.gov.au/energy/sustainable/renewable/wind

[2] AWEA, *Small Wind Turbine Global Market Study: Year Ending 2008*.

[3] Ibid, p. 5.

[4] Kwartin et al., *An Analysis of the Technical and Economic Potential for Mid-Scale Distributed Wind*, NREL, December 2008, p. 41.

[5] Southwest Windpower, "Skystream 3.7: 2.4 kW Residential Power Appliance".

[6] http://www.northernpower.com/wind-power-basics/faq.php#WhatMakesAGoodWindSite

7 http://dsireusa.org/summarytables/rrpre.cfm

8 Ibid.

[9] Kwartin et al., p. 54

[10] Kwartin et al., p. 61

[11] Forsyth, T., and Baring-Gould, I., "Distributed Wind Market Applications," NREL, November 2007, p. 5.

[12] DOE, *Commercial Sector Demand Module of the National Energy Modeling System: Model Documentation 2009*, DOE/EIA-M066(2009), May 2009, pp 40-44.

[13] American Wind Energy Association, *AWEA Small Wind Turbine Performance and Safety Standard, (AWEA Standard 9.1 – 2009)* © The American Wind Energy Association, 2009.

[14] http://www.smallwindcertification.org/index.html

[15] Smith, Joe, "NREL Small Wind Technology Update," AWEA Small & Community Wind Conference & Exhibition, November 5, 2009, Detroit, MI, and manufacturer literature.

[16] Sagrillo, Mick, "Size Matters!" *Windletter*, 28(3); AEP data:

a. Bergey Skystream 3.7, 3-CMLT-1338-01 REV F 1-09

b. "Power Your Dream With the Wind", Bergey Windpower, accessed May 2010.

c. “Entegrity Wind Systems: Commercial Wind Energy Provider and Manufacturer of the EW50”, 2009.

d. “Northwind 100: Community Scale Wind Turbine”, Northern Power Systems, 2009.

[17] Frick, Bob, untitled presentation, AWEA Small & Community Wind Conference & Exhibition, November 5, 2009, Detroit, MI.

[18] Wilke, Steve, “The Evolution of the Bergey Excel wind turbine,” AWEA Small & Community Wind Conference & Exhibition, November 5, 2009, Detroit, MI.

[19] Kruse, Andy, personal communication, AWEA Small & Community Wind Conference & Exhibition, November 5, 2009, Detroit, MI.

[20] AWEA, *Small Wind Turbine Global Market Study: Year Ending 2008*, p. 10.

[21] Ibid, p. 15.

[22] U.S. Department of Energy, *20% Wind Energy by 2030: Meeting the Challenges,* Proceedings of the Workshop, October 6-7, 2008, pp. 13-25.

[23] Kwartin et al., pp. 33-34, for commercial/industrial turbines and unpublished data for residential turbines. Values in Table 7 represent a 2/3 weighting for residential scale turbines and a 1/3 weighting for commercial/industrial scale turbines.

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Headquarters
ICF International
9300 Lee Highway
Fairfax, Virginia 22031
www.icfi.com

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