**Attachment No. 4**

**FIGURE OF MERIT – COST OF ENERGY**
**Distributed Wind Generation**
03/9/2017

This attachment describes the method and assumptions that shall be used to define and support economic figures of merit for wind turbines used in distributed applications, behind the meter. The figure of merit is levelized cost of energy (LCOE), calculated using National Renewable Energy Laboratory (NREL) assumptions for conditions at a reference site. This figure of merit will be used to evaluate an improvement in technology; as such, *costs not associated with the manufacturing of the wind turbine component/installation (i.e., profit, training, dealer fees) shall not be included in individual component costs, but rather in the "other" categories as defined below*. There is an accompanying spreadsheet with all of these calculations embedded.

**Assumptions**
NREL has made several assumptions to differentiate the LCOE for distributed wind turbines (DWT) from the basis of comparison used for large scale utility wind plants as the typical wind resources, financing structure, and tax treatments are quite different. These assumptions shall be used for the reference site. Calculations that are made using other assumptions must clearly show which assumptions have been changed and their new values.

1. Annual average wind speed at hub height of 6.0 m/s with a Rayleigh distribution.
2. Economic parameters: constant January 2017 dollars, FCR=7.4%

**Levelized Cost of Energy**
The primary figure-of-merit is the LCOE, which is to be provided in constant, January 2017 dollars. LCOE is calculated for a wind power plant (or an individual turbine installation), using the following equation:

$$LCOE = \frac{(FCR \times ICC) + AOE}{AEP_{net}}$$

where:

| | | |
|---|---|---|
| LCOE | ≡ | Levelized Cost of Energy (\$/kWh) |
| FCR | ≡ | Fixed Charge Rate = (0.074) |
| ICC | ≡ | Installed Capital Cost (\$) |
| $AEP_{net}$ | ≡ | Net Annual Energy Production (kWh/yr) |
| AOE | ≡ | Annual Operating Expenses (\$/kWh) |
| | ≡ | O&M + LRC |
| O&M | ≡ | Levelized O&M Cost (\$/kWh) |
| LRC | ≡ | Levelized Replacement/Overhaul Cost (\$/kWh) |

**Fixed Charge Rate**
A fixed charge rate (FCR) allows LCOE estimates by relying on a single coefficient. For wind turbines in distributed applications the FCR is calculated to produce the annual cost to the owner assuming a 20 year loan at an interest rate of 4.0%.[1] The resulting fixed charge rate is 7.4%. This is taken as the cost of capital for homeowner investments in energy generation and the cost for other customers and turbine sizes should not be significantly different. FCR is generally

[1] The interest rate is based on a $100k home equity line of credit (as available from Key Bank, 3/9/17).

representative of a specific ownership and cash flow structure and may vary over time. However, a fixed value is required for comparisons across technologies. Due to the diversity of financing structures applied by the wind industry today, the FCR used in this analysis is not indicative of what any particular project may experience, but is a baseline for comparing cost metrics for different turbines.

**Initial Capital Cost**

The Installed Capital Cost is the sum of the Turbine System Cost and the Balance of Station Cost. Neither cost should include financing fees, because these are added through the fixed charge rate. The Turbine System Cost shall be supported by a tabular listing of component costs. Costs shall be based on a full scale manufacturing volume[2]. In estimating the cost of components manufactured in-house, assembly labor and manufacturing overhead shall be included. The following breakdown of component costs shall be used where applicable. As mentioned above, costs not associated with the manufacturing and installation of the wind turbine (i.e., profit, training, dealer fees, etc.) shall not be included in component costs, but rather in the "other" category. The "other" category is intended as a catchall category to bring the total cost up to what a consumer would pay. This includes components not accounted for in other categories, as well as any other soft costs such as profit, training, fees etc. In other words, all costs that the owner of the turbine pays should be covered by adding any cost not included in the itemized list into the other line at the bottom. This list is representative and may not be inclusive; ***<u>proposers are encouraged to include a list that supports their turbine design, in addition to the applicable information below.</u>***

| **Turbine System Costs** | **Baseline** | **Proposal** | **End of Project** |
|---|---|---|---|
| Turbine rotor assembly | | | |
| Turbine nacelle assembly (includes generator) | | | |
| Electrical system (inverter/controller and related electronics) | | | |
| Tower and tower hardware | | | |
| Shipping and delivery | | | |
| Extended warranty (define # of years) | | | |
| Other (difference between costs above and cost to customer) | | | |
| **Total Cost to Consumer** | | | |

The Balance of Station Cost shall be supported by a tabular listing of the costs shown below. As mentioned above, costs not associated with the manufacturing and installation of the wind turbine (i.e., profit, training, dealer markup, etc.) shall not be included in component costs, but rather in the "other" category. The "other" category is intended as a catchall category to bring the total cost up to what a consumer would pay. This includes components not accounted for in other categories, as well as any soft costs such as profit, training, fees etc. This list is representative and may not be inclusive; ***<u>proposers are encouraged to develop a list that supports their turbine design in addition to the applicable information below.</u>***

[2] An arbitrary volume of 50 turbines per year is reasonable for a full scale manufacturing throughput.

| Balance of Station Costs | Baseline | Proposal | End of Project |
|---|---|---|---|
| Wind resource and site assessment, and feasibility studies | | | |
| Zoning approval, permits and licenses, including environmental assessments and engineering work required for these approvals | | | |
| Project engineering and design not directly done for permitting or zoning | | | |
| Site preparation, including roads, grading and fences | | | |
| Electrical infrastructure including wire run (labor, materials, and equipment) | | | |
| Foundation cost (labor, materials, and equipment) | | | |
| Installation including assembly, erection, and commissioning costs (includes crane) | | | |
| Wind turbine monitoring equipment (if applicable) | | | |
| Other project construction costs | | | |
| Sales tax | | | |
| Construction contingency | | | |
| Other (difference between costs above and cost to customer) | | | |
| **Total Cost to Consumer** | | | |

**Annual Operating Expenses**

*Levelized O&M Cost*

Operations and Maintenance Cost (O&M) is a component of Annual Operating Expenses. The O&M Cost shall include, and be supported by, a tabular listing of the following annual costs:

| Operations and Maintenance Costs | Baseline | Proposal | End of Project |
|---|---|---|---|
| Labor, parts and supplies for scheduled turbine maintenance | | | |
| Labor, parts and supplies for unscheduled turbine maintenance (include expenses covered by warranty) | | | |
| Other (define) | | | |
| **Total Cost to Consumer** | | | |

Because O&M costs can vary by year, an annual average value shall be used as a reasonable approximation of the long-term costs. Thus, the levelized O&M cost calculation is:

$$\text{O\&M} = \frac{\text{Yearly O\&M Cost (in 2017 dollars)}}{\text{AEP}_{\text{net}}}$$

*Levelized Replacement/Overhaul Cost*

Levelized Replacement/Overhaul Cost distributes the cost of major replacements (such as gearboxes, blades and other high cost components) and overhauls over the life of the wind turbine. Add lines to the table as required. This cost shall be supported by a tabular listing of:

| Levelized Replacement/Overhaul | Baseline | Proposal | End of Project |
|---|---|---|---|
| For each replacement or overhaul, indicate the year in which it is required relative to the year of installation | | | |
| For each replacement or overhaul, including parts, supplies and labor, provide the cost in current year dollars for the year of the replacement or overhaul | | | |

Downtime leading up to and during replacements and overhauls shall be included in the determination of overall turbine availability.

**Net Annual Energy Production**

The Net Annual Energy Production shall be calculated for one Reference Site, using wind-turbine performance specifications, estimated energy losses, and turbine availability. AEP calculations shall be supported by a tabular listing of the parameters shown below. Values in parentheses shall be used for the Reference Site. There is an accompanying spreadsheet with all of these calculations embedded.

- Reference Site #1: annual average wind speed at a height of 30m = (6 m/s)
- Vertical wind-shear exponent = (0.25)
- Wind distribution table or specification = (Rayleigh)

Generic Annual Energy Production shall be calculated using the methodology described in the latest draft[3] of the International Electrotechnical Commission (IEC) Standard 61400-12-1. For calculations of LCOE, the wind speed range may be divided into 1.0 m/s bins rather than the IEC-specified 0.5 m/s bins. The following equations shall be used.

$$AEP = N_h \sum_{i=1}^{N} [\, F(V_i) - F(V_{i-1})] \, [(P_i + P_{i-1}) / 2]$$

where:

- $AEP \equiv$ Annual Energy Production (kWh/yr/turbine)
- $N_h \equiv$ Number of hours in one year (8760)
- $N \equiv$ Number of wind speed bins
- $V_i \equiv$ Normalized and averaged wind speed in bin (i) (m/s)
- $P_i \equiv$ Normalized and averaged power output in bin (i) (kW)

and:

$$F(V) = 1 - \exp\,[-\pi/4 \times (V/V_{ave})^2]$$

[3] IEC 61400-12-1, Wind Turbines, Part 12-1: Power performance measurements of electricity producing wind turbines, 2005

| | | | |
|---|---|---|---|
| where: | $F(V)$ | $\equiv$ | Rayleigh cumulative probability distribution function for wind speed |
| | $V$ | $\equiv$ | Actual wind speed (m/s) |
| | $V_{ave}$ | $\equiv$ | Annual average wind speed at hub height (m/s) |

The summation is initiated by setting $V_{i-1}$ equal to $V_i$ - 0,5 m/s and $P_{i-1}$ equal to 0,0 kW.

Turbine Performance shall be tabulated as electrical power output at the bus bar versus wind speed at hub height. The table shall show power output for wind speeds from 0 to 30.5 m/s in 1.0 m/s increments starting with 0.5 m/s. If the table is based upon measurements, normalizations and averaging using the IEC methodology, it shall identify which bins include "measured" data (based on three, 10-minute data sets) and which bins are extrapolations of measured data. If the table is based on projected performance, the rotor configuration and analysis method (e.g. PROP) shall be clearly stated.

Net Annual Energy Production shall account for energy losses and availability as follows. The supplementary spreadsheet has all of these calculations built in.

$$AEPnet = AEP \times (1 - EL) \times \text{Availability of turbine}$$

| | | | |
|---|---|---|---|
| where: | EL | = | Product of individual energy losses (% losses expressed as a decimal) |
| | EL | = | 1 - (1 - Lsoiling) x (1 - Lcontrol) x (1 - Lcollect) |
| | Lsoiling | = | Blade soiling losses as a percent of energy production |
| | Lcontrol | = | Controls and miscellaneous losses |
| | Lcollect | = | Grid availability losses. |

Energy Losses and Availability shall be specified in a tabular listing. If the power curve is a measured power curve that included control and collection losses, these factors are entered as zero. Assume grid availability losses of 4%. Availability is the ratio of the number of hours that the turbine was capable of operating during a certain period (excludes the number of hours that it could not operate because of grid outage situations) to the total number of hours in the period. If better data are not available, a turbine availability of 95% shall be assumed.

**Wind Resource Regimes**

Using the methods described above, LCOE will be calculated at one wind regime – outlined below, with a Rayleigh distribution (k=2). Use of the accompanying spreadsheet with all of these calculations embedded is recommended. This spreadsheet has built in adjustments for hub heights other than 30 meters.

The following equation shall be used to compute the wind speed as a function of height above the ground. For the LCOE Reference Site, the wind shear exponent $\alpha = 0.25$.

$$V(z) = V30m\,(z/30m)^{\alpha}$$

Note that turbulence levels and extreme gust conditions used for design analyses are not described by the wind-speed probability distributions given above. If required these values shall be clearly defined by the Subcontractor and reported to NREL in appropriate deliverable reports.

**Total**
All calculated numbers from the above categories should be summarized in the table below and used to calculate an LCOE.

| **LCOE Summary** | **Baseline** | **Proposal** | **End of Project** |
|---|---|---|---|
| Turbine Component ($) | | | |
| Balance of Station ($) | | | |
| Annual Operating Expenses ($/kWh) | | | |
| Annual Energy Production (kWh/yr) | | | |
| **LCOE** ($/kWh) | | | |