



Reference Manual for the System Advisor Model's Wind Power Performance Model

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1 Executive Summary

This manual describes the National Renewable Energy Laboratory's System Advisor Model (SAM) wind power performance model. The model calculates the hourly electrical output of a single wind turbine or of a wind farm. The wind power performance model requires information about the wind resource, wind turbine specifications, wind farm layout (if applicable), and costs. In SAM, the performance model can be coupled to one of the financial models to calculate economic metrics for residential, commercial, or utility-scale wind projects. This manual describes the algorithms used by the wind power performance model, which is available in the SAM user interface and as part of the SAM Simulation Core (SSC) library, and is intended to supplement the user documentation that comes with the software.

2 Variables and Naming Conventions

This chapter describes the abbreviations, variables, and naming conventions used in this manual.

2.1 Abbreviations

Table 1. Abbreviations used in this manual

Abbreviation	Description
API	application programming interface
NREL	National Renewable Energy Laboratory
SAM	System Advisor Model
SDK	software development kit
SSC	SAM Simulation Core

2.2 Variable Names

This manual describes three types of variables.

- Letters and subscripts to represent variables in equations in the algorithm descriptions.
- Variable names **in bold font** are names of inputs and results from the SAM user interface.
- Variable names **in Courier font** are names of inputs and outputs in the SAM Simulation Core (SSC).

Table 3 lists the variables used in this manual, and Table 2 lists the subscripts used with variables.

Table 2. Subscripts Used in Variable Names

Subscript	Description
h	turbine hub height
i	wind speed bin in the Weibull resource distribution
j	hour in an 8760 hourly data set for one year
m	power curve rated power point

The variable names in this document are described in Table 3. For those variables that appear in the SAM user interface, their name appears in the table's "Name in SAM" column. Names of variables that are either inputs or outputs to the SSC **windpower** module are listed under "Name in SSC."

Table 3. Variable Names and Descriptions (For a complete list of SAM and SSC variables, see the variable index in Chapter 11 of this manual.)

Name	Description	Name in SAM	Name in SSC	Units
C_{Pmax}	Maximum power coefficient	Max Cp	max_cp	-
C_t	Wind turbulence coefficient	Turbulence Coefficient	turbul	-
D	Rotor diameter	User Defined Rotor Diameter	rotor_di	m
h	Hub height	Hub Height	hub_ht	m
K	System capacity factor	Capacity Factor	-	-
k	Weibull shape parameter	Weibull K Factor	weibullK	-
L	Fixed loss factor	Wind Farm Losses	lossp	%
$P(V_i)$	Turbine rated power at wind speed V_i	Turbine Output ^(c)	pc_power	kW
$P_{wf,j}$	Wind farm hourly electrical output	-	farpwr	
$Q(V_i)$	Turbine electrical output at wind speed V_i	Annual Energy @ wind speed (kWh) ^(c)	turbine_output	kWh
Q_{sys}	System annual output after performance adjustments	Annual Energy ^(a)	annual_e_net_delivered	kWh
Q_{wf}	Wind farm annual output before performance adjustments	-	farpwr	
V_{50}	Wind speed at 50 m	Average Annual Wind Speed (@ 50 meters)	resource_class	m/s
V_i	Turbine power curve wind speed	Wind Speed ^(c)	pc_wind	m/s
$V_{tip\ max}$	Maximum tip speed	Max Tip Speed	-	m/s
V_0	Turbine power curve cut-in wind speed	Cut-in Wind Speed	cutin	m/s
α	Wind shear coefficient	Shear Coefficient	shear	-
λ	Weibull scale parameter	- ^(b)	-	m/s
λ_{max}	Maximum tip speed ratio	Max Tip Speed Ratio	-	-

Table 3 Notes:

(a) An output of the SSC **annualoutput** module.

(b) SAM calculates the Weibull scale parameter from the average annual wind speed at 50 meters input.

(c) These variables are available in SAM on the Results page, **Tables, Data: 161 values**.

3 Introduction

This reference manual describes the wind power performance model in the National Renewable Energy Laboratory's System Advisor Model (SAM) Version 2013.9.20 (SIL 3.0.1, SSC 33).

SAM is a desktop application designed for renewable energy analysts to evaluate system design and project financial options. SAM's wind power performance model is also available to software developers as the **windpower** module in the SAM Simulation Core (SSC) application programming interface (API) included in the SAM software development kit (SDK).

NREL provides both the SAM application and SDK for free from the SAM website at <https://sam.nrel.gov/>. More information about the software development tools can also be found on the SAM website.

For SAM users, this reference manual supplements the SAM user documentation in SAM's Help system.¹ For software programmers, it supports development of applications that use the API to the **windpower** module.

3.1 SAM Overview

The System Advisor Model (SAM) is a desktop application designed to facilitate techno-economic analysis of renewable energy projects. It is a decision-making tool for project developers, financial analysts, policymakers, and energy researchers. SAM can model grid-connected power systems that use wind, photovoltaic, concentrating solar power, solar hot water, biopower, or geothermal electricity generation technologies.

To model a renewable energy project in SAM, you choose a performance model to represent the system, and a financial model to represent the project's financial structure. You then specify values on the input pages to describe the physical characteristics of the system and financial parameters of the project. All of the input variables are populated with default values so that you can start generating preliminary results before you have collected all of the data for your project. After specifying inputs, you run a simulation and the performance model makes a series of 8,760 hour-by-hour calculations to calculate the system's hourly electrical output over a one-year period². The financial model uses the hourly electric generation profile and user inputs such as installation and operating costs, electricity price, taxes and incentives, and debt parameters to calculate the project's annual cash flows over a multi-year period [1]. SAM displays results from both the performance and the financial models in tables and graphs, and provides options for exporting the results for use in reports and presentations.

SAM's advanced simulation options facilitate parametric, sensitivity, and statistical studies that involve multiple simulation runs. The SamUL scripting language is a built-in programming language that makes it possible to automate repetitive or complex modeling tasks.

¹ SAM's user documentation is available as a Help system in the user interface, and as both a web document and PDF document on the SAM website at <https://sam.nrel.gov/content/resources-learning-sam> (accessed October 11, 2013).

² This description is generally true for SAM's performance models, with the exception of the wind power model's Weibull distribution option for the wind resource which calculates a statistical distribution of the system's annual output instead of time-series values (see Chapter 4.2).

SAM can model both distributed generation and central generation projects. The residential and commercial financial models are for distributed generation projects that buy and sell electricity at retail rates, and use renewable energy to supplement electricity from the grid to meet a building's or facility's electric load. The utility financial models are for central generation projects that sell all of the electricity generated by the system at a price negotiated through a power purchase agreement.

This manual describes SAM's wind power performance model. It does not describe the financial models or other simulation options available in SAM. For an overview of SAM's financial models, see the Financial Models topic in SAM's Help system [https://www.nrel.gov/analysis/sam/help/html-php/index.html?fin_overview.htm].

3.2 SAM Simulation Core (SSC)

The SAM Simulation Core (SSC) is the library of software modules that SAM uses to run simulations. The SSC's application programming interface (API) makes it possible for software developers to develop their own applications using SAM's underlying performance and financial models.

The SAM Software Development Kit (SDK) is a collection of software development tools that make it possible to write programs in C++, C#, Java, MATLAB, or python that run SAM Simulation Core (SSC) modules. The SDK includes the API to the **windpower** simulation module described here, and the APIs to SAM's other modules. Note that the SDK does not provide access to the module's source code.

Table 3 and the Index of SAM and SSC Variable Names on Page 27 show where a specific **windpower** module variable is mentioned in this manual.

3.3 Model Applications and Limitations

SAM's performance models are intended for project pre-feasibility level analysis. The wind performance model can provide a very preliminary estimate of the expected hourly electricity production and capacity factor over a one-year period for a single wind turbine, small wind project, or large wind farm. The financial model uses the sum of the hourly values as an estimate of the project's production in its first year, and extends the estimate over a period of several years to calculate metrics such as levelized cost of energy, project net present value, power purchase agreement (PPA) price and internal rate of return for utility projects, and total electricity savings and payback period for residential and commercial projects.

SAM's wind performance model requires information that describes the wind resource at the project location, a set of inputs to describe the wind turbine performance characteristics, and inputs to describe the layout of the turbines for projects with more than one turbine. The quality of the performance model's predictions depends on the quality of these inputs.

SAM's approach to modeling a wind farm includes a number of simplifying assumptions described in Chapter 8. Although SAM does calculate wake effect losses due to the effect of upwind turbines on their downwind neighbors, more detailed wind analysis models are better suited than SAM for detailed analysis of the impact of farm layout, topography and terrain on wind farm performance.

SAM's hourly simulation time step provides enough temporal resolution to offer insight into the effect of daily and seasonal resource variation on the system's output with sufficient detail for project techno-economic modeling, but not for detailed engineering design modeling such as physical stresses on turbine components or electrical transients.

3.4 General Modeling Approach

The SAM wind performance model algorithm consists of the four primary steps described briefly below and in more detail in the chapters that follow.

Step 1. Characterize the Wind Resource: The wind power model uses wind resource data either from an hourly data file or defined as a Weibull statistical distribution.

Step 2. Specify the Wind Turbine's Power Curve: SAM models wind turbine performance using a power curve- either a user-specified power curve table or one that SAM calculates from a set of turbine characteristics.

Step 3. Define the Wind Farm Layout: The wind farm is a two-dimensional array of coordinates for each turbine's location with additional inputs used to calculate wake effect losses.

Step 4. Calculate the Wind Farm Electrical Output: SAM's hour-by-hour simulation calculates the system's electrical output in kWh for each of the 8,760 hours in one year.³ SAM reports the hourly values on the Results page along with monthly and annual totals in tables and graphs that can be exported to other applications.

4 Wind Resource Data Options

The wind resource data provides information about the kinetic energy available in the wind at the wind turbine's location and hub height. The amount of available energy depends on the wind speed and air density and varies with time. The options on SAM's **Wind Resource** input page determine how SAM characterizes the wind resource:

- **Weather file (Wind Resource by Location)**, Chapter 4.1: The wind resource data comes from a weather file with 8,760 hourly values for wind speed, direction, air temperature, and air pressure at one or more turbine hub heights.
- **Weibull distribution (Wind Resource Characteristics)**, Chapter 4.2: The wind resource is represented by a statistical distribution characterized by an annual average wind speed value and Weibull K factor. This option only works with a single turbine because there is insufficient data to model wind farm wake effects.

In the SSC **windpower** module, variable `model_choice = 0` is equivalent to the Wind Resource by Location option in SAM, and `model_choice = 1` is equivalent to the Weibull distribution option.

³ The financial models assume that this annual generation profile applies to all years in the project life. They apply a set of optional performance adjustment factors to account for system availability, curtailment, and any annual decrease in system output. See the user documentation for details (or online at https://www.nrel.gov/analysis/sam/help/html-php/index.html?fin_annual_performance.htm, last visited October 10, 2013).

4.1 Wind Resource Data from a Weather File

When the option on SAM's **Wind Resource** input page is **Wind Resource by Location**, SAM reads wind resource data from the weather file highlighted in the weather file list. The **Folder Settings** options determine where on your computer SAM looks for the weather files.

In the SSC **windpower** module, the variable **file_name** stores the weather file's complete path and name, for example **file_name = "c:\users\paul\weather data\my_weather_file.srw"** refers to a weather file named *my_weather_file.srw* in the *c:\users\paul\weather\data* folder.

4.1.1 The SRW Weather File Format

The wind performance model reads wind resource data from a weather file in the SRW format⁴, which is a text format with comma-separated values. You can find examples SRW files in the default weather file folder (*c:\SAM\2013.9.20\weather* in Windows), and a description of the format in the "Weather File Formats" topic of SAM's help system [2].

The SRW file format is designed to be flexible enough to allow you to create files with your own data. See the SAM help topic for more information on using or creating SRW files.

4.1.2 Representative Typical Weather Files

The SAM installation package includes a set of 39 weather files developed for NREL by AWS Truepower that contain wind speed, wind direction, ambient temperature, and atmospheric pressure data at 50, 80, and 110 meters above the ground. They are "representative" because they are for locations with topography and weather combinations that represent regions of the U.S. where large-scale wind farms are typically developed. The files are "typical" because they represent the wind resource over a period of 14 years between 1997 and 2010 [3].

4.1.3 Weather Files from the NREL Wind Integration Datasets

This data is available for 2004, 2005, and 2006 from different sources for the Western United States and Eastern United States. The Western Wind Dataset has data developed by NREL and 3Tier for over 32,000 locations in the Western United States. The Eastern Wind Data set has data developed by NREL and AWS Truepower for 1,326 locations in the Eastern United States. When you download data from these datasets from within SAM, SAM converts the data into an SRW file.

The **Download weather file** button on SAM's **Wind Resource** input page when it is in **Wind Resource by Location** mode automatically downloads files from the NREL Wind Integration Datasets database. The SSC **windpower** module does not have a function for accessing this database, but these files can be downloaded externally and used with the SSC module.

4.2 Wind Resource Data as a Weibull Distribution

For analyses that do not require the detail of time series wind resource data, SAM's Weibull distribution option represents the wind resource as a statistical distribution characterized by a single average annual wind speed and Weibull K factor. This option may be useful for very

⁴ Older versions of the model used a different file format than that used in the SRW file extension.

preliminary project feasibility studies before time series data is available, or for analyses involving parametric studies on a single annual average wind speed value or the shape of wind speed distribution over the year.

SAM disables the variables on SAM's **Wind Farm** input page with the Weibull Distribution wind resource option because the option provides no information about wind direction that SAM needs to model wake effect losses in a wind farm.

4.2.1 Weibull Distribution

The Weibull probability distribution function determines the probability that a given wind speed value will occur over a given period:

$$f(V) = \frac{k}{\lambda^k} \times (V)^{k-1} \times e^{-(V/\lambda)^k} \quad (1)$$

where

$f(V)$ = Weibull wind speed probability distribution function

V = wind speed

k = dimensionless shape parameter, **Weibull K Factor** in SAM, **weibullK** in the SSC **windpower** module

λ = scale parameter in m/s, **Average Annual Wind Speed (@ 50 meters)** in SAM, **resource_class** in SSC

The turbine's elevation above sea level is an input for the "turbine power curve from characteristics" option described in Chapter 5.2. It has no effect on the wind speed distribution curve.

4.2.2 Wind Resource Curves

When the **Wind Resource** input page is in **Wind Resource Characteristics** mode, the graph shows the Weibull wind speed distribution that SAM uses for simulations:

- Weibull wind speed distribution (**Weibull**): The wind speed probability distribution function defined by the Weibull factors you specify on the **Wind Resource** input page (see Equation 1). This is the distribution that SAM uses to calculate the turbine's total annual electrical output.

The graph also shows two other reference probability distribution curves that SAM does not use in simulations:

- Rayleigh wind speed distribution (**Rayleigh**): Another commonly-used probability distribution function for wind resource analysis. The Weibull and Rayleigh distributions are the same when $k = 2$.
- Weibull Betz turbine electrical output distribution (**Weibull Betz**): This represents the distribution of power for a theoretical "Betz turbine" as described in [4].

When you specify the turbine from characteristics (see Chapter 5.2), the graph displays three additional curves from an implementation of the NREL Wind Turbine Design Cost and Scaling Model described in Chapter 3.5 of [5]. This model is implemented in SAM's user interface and is not available in SSC. SAM does not use these additional curves for simulations. In order to see these curves, you must change the value of one of the input variables on the **Wind Resource** input

page because the graph will only refresh when an input value changes (this behavior may change in future versions of SAM so that the graph updates automatically). The three curves are:

- Weibull coefficient of power turbine electrical output distribution (**Weibull Cp**): Distribution of the modeled electrical output of the turbine with characteristics defined on the Turbine input page.
- Turbine electrical output distribution (**Turbine Energy**): The product of the turbine power and the Weibull probability.
- Hub efficiency distribution (**Hub Eff/10**): The conversion efficiency of the turbine with characteristics defined on the Turbine input page. The efficiency value is divided by 10 so that it fits on the right-hand y-axis.

5 Wind Turbine Model Options

SAM uses a wind turbine power curve to calculate the turbine's electrical output in each time step, given the resource characteristics as described above. The **Turbine** input page provides two options for defining the power curve:

- **Power curve library (Select turbine from a list)**, Chapter 5.1: A pre-defined table of wind speed/turbine output value pairs represents the turbine's performance. When you choose a turbine from the list on the **Turbine** input page, SAM displays the turbine's power curve from the library.
- **Turbine characteristics (Define the turbine characteristics below)**, Chapter 5.2: SAM uses a set of user-specified turbine design parameters to calculate a turbine power curve. You specify values for the parameters on the **Turbine** input page, and SAM calculates and displays the power curve.

5.1 Turbine Power Curve from the Library

SAM's power curve library contains power curve data developed by NREL for the NREL Wind Turbine Cost and Scaling Model described in [4]. NREL developed the power curves from analysis of published performance data, so they do not represent manufacturer data.

The power curve library is not part of the SSC **windpower** module. In the **windpower** module, you specify the wind turbine power curve using the **pc_wind** and **pc_power** input variables, where **pc_wind** is a list of wind speed values included in the power curve in m/s, and **pc_power** is a list of the same length containing the power curve output values in kW.

For most turbines in the library, SAM stores an array of 160 pairs of wind speed and power output values, corresponding to wind speeds in 0.25 m/s increments from 0 to 40 m/s. Table 4 shows an example from the library for a small wind turbine's power curve (note that unlike most turbines in the library, this turbine power curve has fewer than 160 value pairs).

Table 4. Wind Turbine Power Curve for the Bergey Excel S 60 Wind Turbine from the SAM Library.
 Most turbines in the library have 160 data points instead of the 40 for this turbine. This small turbine is nominally rated for 8.9 kW at 11 m/s

V	P(V)	V	P(V)
0	0	21	3
1	0	22	3
2	0	23	3
3	0	24	3
4	0.25	25	3
5	0.8	26	0
6	1.65	27	0
7	2.55	28	0
8	3.65	29	0
9	4.85	30	0
10	6.15	31	0
11	7.5	32	0
12	9	33	0
13	9.5	34	0
14	10	35	0
15	8	36	0
16	6	37	0
17	2.7	38	0
18	3	39	0
19	3	40	0
20	3		

It is possible to run SAM with a power curve for a turbine that is not included in the library by creating a user library and adding power curve data for one or more turbines to the library. SAM's library editor is described in the "Libraries" Help topic [5].

5.2 Turbine Power Curve from Characteristics

The Turbine Characteristics option uses a set of user-specified turbine characteristics to calculate the turbine's power curve. SAM's algorithm, described below, is adapted from the method described for the NREL Wind Turbine Design Cost and Scaling Model described in Chapter 3.5 of [4] and also in [8].

In **Define the turbine characteristics below** mode, SAM calculates the turbine power curve in the user interface. These calculations are not part of the SSC **windpower** module.

The algorithm divides the power curve into the five regions shown in Figure 1, and uses empirical equations to calculate the curve in each region.

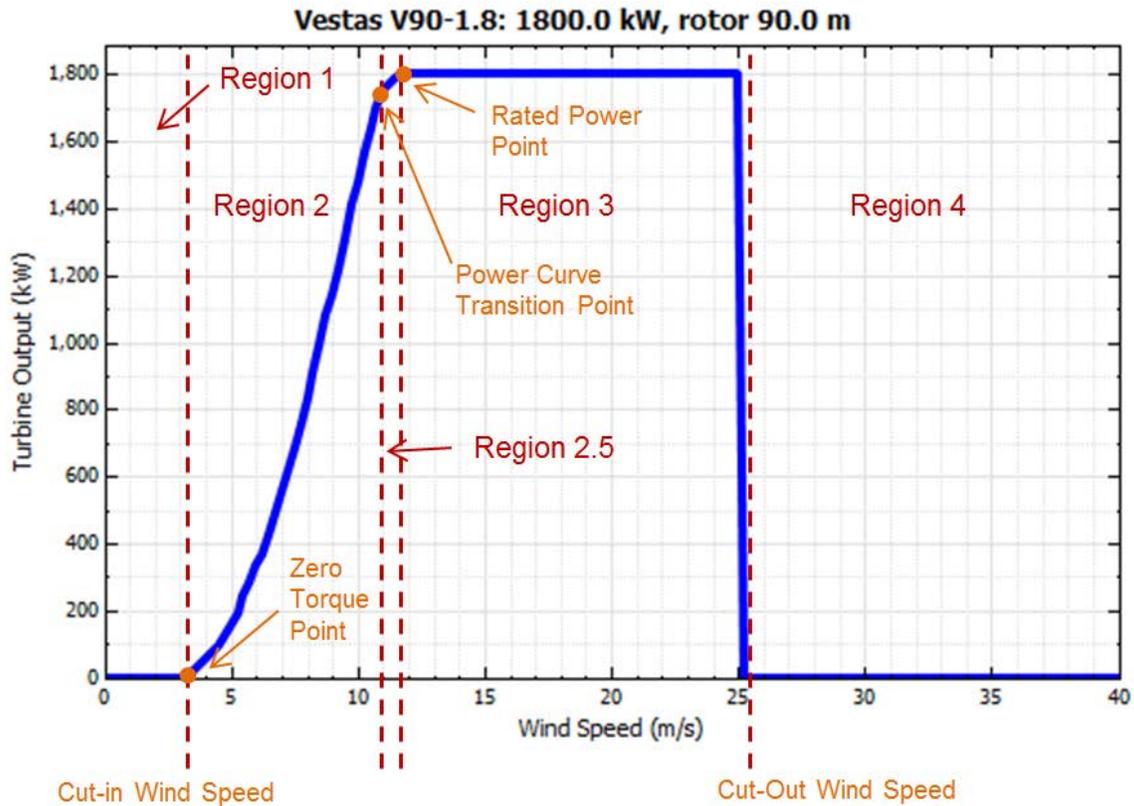


Figure 1. Power Curve Diagram (Example from SAM)

Region 1: Below the cut-in wind speed. The point on the power curve at the boundary between Regions 1 and 2 corresponds to the zero-torque point of the power curve (ω_0, T_0).

Region 2: Above the cut-in wind speed but below the power curve transition point (ω_t, V_t). In this region, the turbine power increases with the cube of the wind speed, so Region 2 is sometimes called the cubic region.

Region 2.5: The linear transition between Region 2 and Region 3. It begins at the power curve transition point (see Figure 1) and ends at the rated power point (ω_m, V_m). In an ideal power curve, Region 2.5 would not exist, but real power curves behave slightly differently than the ideal power curve, hence the introduction of an empirical Region 2.5. Note that this region is called Region 2.5 following the convention of the Cost and Scaling Model.

Region 3: Above the rated wind speed but below the cut-out speed. The turbine operates at its rated capacity in this region.

Region 4: Above the cut-out speed.

The drivetrain efficiency is the ratio of the turbine's AC electrical output to the mechanical energy of the spinning rotor, as defined in Section 8.3.5 of [5]. The Cost and Scaling Model algorithm defines the drivetrain efficiency as described on Page 8 of [8]:

$$\eta = \frac{P_R - (C + LP_R + QP_R^2)}{P_R} \quad (2)$$

where

η = drivetrain efficiency

C = constant turbine losses

L = linear turbine losses

Q = quadratic turbine losses

P_R = power ratio (ratio of produced power to rated power)

Constant losses are independent of power production and include transformer losses and other electrical conversion losses. Linear losses scale directly with power production. Quadratic losses depend on the square of the power production. The most common quadratic loss is copper losses at constant voltage (resulting from the well-known $P = I^2R$ equation, where I is current and R is resistance). The losses are dependent on the type of drive train as shown in Table 5 [8].

The algorithm assumes an ideal power ratio of one, $P_R = 1$, so that Equation 2 simplifies to:

$$\eta = 1 - (C + L + Q) \quad (3)$$

Table 5. Drivetrain loss characteristics by drivetrain design

Drivetrain Design	C	L	Q	Total Losses
3 Stage Planetary	0.013	0.085	0	0.098
Single Stage	0.013	0.037	0.061	0.11
Multi-Generator	0.015	0.044	0.058	0.12
Direct Drive	0.010	0.020	0.069	0.099

The rated hub power is given by:

$$P_{h,m} = \frac{P_m}{\eta} \quad (4)$$

where

$P_{h,m}$ = calculated rated hub power in W

P_m = turbine rated power in W, **User Defined Rated Output** on the **Turbine** input page

η = drivetrain efficiency

And the rated hub rotor speed is:

$$\omega_m = \frac{2V_{tip\ max}}{D} \quad (5)$$

where

ω_m = rated hub rotor speed in revolutions per second

$V_{tip\ max}$ = maximum tip speed in m/s, **Max Tip Speed** on the **Turbine** input page

D = rotor diameter in m, **User Defined Rotor Diameter** in SAM

The rated torque T_m in N-m is then:

$$T_m = \frac{P_{h,m}}{\omega_m} \quad (6)$$

The calculations for power curve regions 2.5, 3, and 4 require another parameter, the variable speed torque constant [4]:

$$k = \frac{\pi \rho D^5 C_{Pmax}}{64 \lambda_{max}^3} \quad (7)$$

where

k = variable speed torque constant in $\text{kg} \cdot \text{m}^2$

C_{Pmax} = maximum turbine coefficient of power, **Max Cp** on the **Turbine** input page

λ_{max} = the maximum tip speed ratio, **Max Tip Speed Ratio** in SAM

ρ = air density in kg/m^3 , from Equation 8

The air density at any altitude is:

$$\rho = \frac{p_0 \times \left[1 - \frac{L_b \times s}{T_0} \right]^{L_b \times R_{sp} \frac{g_0}{T_0}}}{R_{sp} \times (T_0 + L_b \times s)} \quad (8)$$

where

p_0 = mean sea level atmospheric pressure (101,325 Pa)

L_b = standard temperature lapse rate (-0.0065 K/m)

s = elevation above sea level in meters, either from the weather file, or **Elevation Above Mean Sea Level** on the **Wind Resource** input page

T_0 = ICAO standard temperature (288.15 K)

g_0 = standard gravity (9.80665 m/s^2)

R_{sp} = specific gas constant for dry air (287.058 $\text{J}/\text{kg} \cdot \text{K}$)

The transition points between power curve regions are the zero torque point, power curve transition point, rated power point, and cut-out wind speed (given in turbine specifications) shown in Figure 1.

The Region 2 rotor speed where torque is zero is given by:

$$\omega_0 = \frac{\omega_m}{1 + \frac{m}{100\%}} \quad (9)$$

where

ω_0 = rotor speed at zero torque

ω_m = rotor speed at rated torque, from Equation 5

m = the slope of Region 2.5 of the power curve, assumed to be 5%

The sloped sections of the power curve in Region 2 and Region 2.5 intersect at the power curve transition point:

$$\omega_t = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad (10)$$

where

ω_t = rotor speed at transition point

$a = k$ from Equation 7

$$b = -\frac{T_m}{\omega_m - \omega_0}$$

$$c = \frac{T_m \omega_0}{\omega_m - \omega_0}$$

The wind speed in m/s at the transition point is:

$$V_t = \frac{\omega_t D}{2\lambda_{max}} \quad (11)$$

And the power in W at the transition point is:

$$P_t = k\omega_t^3 \quad (12)$$

The wind speed at the rated power point in m/s is given by:

$$V_r = \frac{1}{3} \left(\frac{2P_{h,m}}{\rho \frac{\pi D^2}{4} C_{Pmax}} \right)^{1/3} + \frac{2}{3} \left(\frac{1}{1.5 \rho \frac{\pi D^2}{4} C_{Pmax} V_t^2} \times (P_{h,m} - P_t) + V_t \right) \quad (13)$$

The derivation of Equation 13 is beyond the scope of this manual.

After calculating values for the transition points, the Cost and Scaling Model algorithm calculates hub power and wind speed value pairs to define the entire power curve for wind speeds between 0 and 40 m/s in increments of 0.25 m/s. The hub power calculation used at each speed depends on the region in which that wind speed falls, which may be determined from comparison to the transition points.

For Regions 1 and 4 (below cut-in speed and above cut-out speed, respectively), the hub power is zero by definition:

$$P_h = 0 \quad (14)$$

In Region 2, hub power is a cubic function of the wind speed:

$$P_h = \frac{k}{1000} \left(\frac{V \lambda_{max}}{D/2} \right)^3 \quad (15)$$

where

P_h = hub power at wind speed V

k = variable speed torque constant from Equation 7

λ_{max} = maximum tip speed ratio, **Max Tip Speed Ratio** from the **Turbine** input page

D = rotor diameter, **User Defined Rotor Diameter** from SAM

In Region 2.5, the hub power at a given wind speed V is interpolated linearly between V_t and V_r calculated in Equations 11 and 13, respectively:

$$P_h = \frac{(V - V_t)}{(V_r - V_t)} (P_{h,m} - P_t) + P_t \quad (16)$$

In Region 3, the hub power is equal to the rated power:

$$P_h = P_{h,m} \quad (17)$$

The Cost and Scaling Model algorithm can now calculate the actual drivetrain efficiency η at wind speed V for non-zero hub power P_h using the actual power ratio, rather than the ideal power ratio used in Equation 2:

$$\eta = \frac{\left(\frac{P_h}{P_{h,m}}\right) - \left(c + L \frac{P_h}{P_{h,m}} + Q \left(\frac{P_h}{P_{h,m}}\right)^2\right)}{\left(\frac{P_h}{P_{h,m}}\right)} \quad (18)$$

Combining the appropriate equation from Equations 14-16 with Equation 18, the turbine power at any wind speed V is then:

$$P = P_h \eta \quad (19)$$

SAM stores these turbine power values in an array of 160 points corresponding to their wind speeds, similar to the power curve of a library turbine. The values are available in SAM after running simulations on the Results page, in **Tables**, under **Data: 161 values as Turbine Power Curve - Rating (kW)** and **Turbine Power Curve - Wind Speed (m/s)**.

6 Wind Turbine Output from a Weibull Distribution

When you run a simulation in SAM with the wind resource defined as a Weibull distribution or the SSC **windpower** module with **model_choice = 1** (see Chapter 4), SAM does not perform a time series simulation, but instead calculates the turbine's electrical output for a series of wind speed “bins.” Each bin is a range of wind speeds on the turbine power curve from the current wind speed (V_i) to the previous wind speed (V_{i-1}).

The number of bins depends on the wind turbine model. Most power curves in SAM's turbine library have 160 wind speed points (every 0.25 m/s from 0-40 m/s), which corresponds to 160 wind speed bins. Some of the turbines in the library have fewer points. When SAM calculates the power curve from turbine characteristics, it uses 160 points.

When you specify the wind resource as a Weibull distribution, there is no information about wind direction, so SAM disables the wind farm inputs and models the system as a single turbine.

6.1 Wind Speed at Turbine Hub Height

To compute the power output for a given wind speed bin, SAM first determines the wind speed at the turbine hub height:

$$V_h = V_{50} \left(\frac{h}{50}\right)^\alpha \quad (20)$$

where

V_h = wind speed at the hub height in m/s

V_{50} = wind speed at 50 m in m/s, **Average Annual Wind Speed (@ 50 meters)** on the **Wind Resource** input page

h = hub height in m, **Hub Height** on the **Turbine** input page

α = shear coefficient, **Shear Coefficient** on the **Turbine** input page

The shear coefficient depends on the terrain, typically ranging from about 0.1 for open water to about 0.3 for hills or mountains. Because V_h describes the average wind speed of the Weibull distribution for the given hub height, the shape parameter for that hub height can be back-calculated using the gamma function Γ [6]:

$$\lambda_h = \frac{V_h}{e^{\log \Gamma(1+\frac{1}{k})}} \quad (21)$$

where

λ_h = Weibull shape parameter (unitless) at hub height h

V_h = average wind speed in m/s at hub height h

k = Weibull k parameter, **Weibull K Factor** on the **Wind Resource** input page, **WeibullK** in the SSC **windpower** module

6.2 Wind Speed Probability

Next, SAM uses the cumulative probability distribution function to predict the probability that the turbine hub wind speed will be a positive number less than or equal to the wind speed V_i (note that the cumulative distribution function is different from the probability distribution function in Equation 1):

$$F(V_i) = 1 - e^{-\left(\frac{V_i}{\lambda_h}\right)^k} \quad (22)$$

where

$F(V_i)$ = Weibull cumulative probability distribution function for wind speed

V_i = wind speed in m/s

k = Weibull k factor, **Weibull K Factor** on the **Wind Resource** input page

λ_h = shape parameter at hub-height h from Equation 21

The probability that the hub wind speed will fall within the current wind speed bin is given by:

$$F(bin) = F(V_i) - F(V_{i-1}) \quad (23)$$

where $F(V_i)$ and $F(V_{i-1})$ = the cumulative probability function at the wind speed in the current bin and previous bin, respectively.

6.3 Turbine Output Probability

Finally, to compute the contribution of this wind speed bin to the total annual electrical output, SAM computes the power for wind speed bin i :

$$P_i = P(V_i) \times F(bin) \times 8760 \quad (24)$$

where

P_i = contribution of wind speed V_i to turbine's total annual electrical output in Wh

$P(V_i)$ = power from the turbine power curve at the wind speed V_i in W

8760 = number of hours in a year

7 Wind Turbine Output from a Weather File

When you use a weather file with time series data for the wind resource data or the SSC **windpower** module with **model_choice = 0** (see Chapter 4.1), SAM calculates a single wind turbine's hourly output using wind speed data from the weather file and the turbine's power curve from either the turbine library (see Chapter 5.1), or calculated from wind turbine characteristics (see Chapter 5.2). SAM then adjusts the turbine output using the air density data from the weather file.

7.1 Wind Speed at Turbine Hub Height

SAM determines the wind speed at the turbine's hub height from the wind speed in the weather file for the given hour. The weather file may contain wind speed data at one or more data heights. If the turbine hub height is the same as one of the data heights in the weather file, SAM uses that wind speed. Otherwise, it determines the data height nearest the hub height and uses the shear coefficient to estimate the wind speed at the hub height:

$$V_{h,j} = V_{0,j} \times \left(\frac{h}{h_0}\right)^\alpha \quad (25)$$

where

$V_{h,j}$ = wind speed at turbine hub height h for hour j

$V_{0,j}$ = wind speed from weather file at data height nearest the turbine hub height for hour j

h = turbine hub height

h_0 = data height (height at which wind speed in weather file was measured) nearest the turbine hub height

α = wind shear factor, **Shear Coefficient** on the **Turbine** input page, or **shear** in SSC **windpower** module

7.2 Turbine Output at Hub Height Wind Speed

To determine the turbine's output in a given hour, SAM finds the hub height wind speed in the turbine power curve table, and looks up the turbine output power for that wind speed. If the hub height wind speed falls between two points in the power curve table, SAM uses linear interpolation to estimate the output:

$$P(V_{h,j}) = \frac{P(V_2) - P(V_1)}{V_2 - V_1} \times (V_{h,j} - V_1) + P(V_1) \quad (26)$$

where

$P(V_{h,j})$ = turbine output at hub height wind speed for hour j

$V_{h,j}$ = hub height wind speed for hour j

$P(V)$ = the turbine output at wind speed V from the power curve

V_1 and V_2 = the next smallest and largest power curve wind speed to the hub height wind speed, respectively

If the wind speed at hub height $V_{h,j}$ for a given hour j is less than the power curve cut-in speed, or greater than the highest wind speed in the power curve, then the turbine output P_j is set to zero. Note that for most of the turbines in SAM's turbine library, the maximum wind speed is 40 m/s, and the cut-out wind speed is between 20 m/s and 25 m/s. For typical wind project locations in the United States, the maximum hourly average wind speed rarely exceeds 25 m/s.

7.3 Turbine Output Adjusted for Air Density

SAM assumes that the wind turbine power curve is for a turbine installed at sea level. The model adjusts turbine output at hub height wind speed for a given hour to the air density at the turbine's location in that hour. The hourly air density depends on the atmospheric pressure value from the weather file:

$$\rho_j = \frac{p_j}{R_{sp} \times T_j} \quad (27)$$

where

ρ_j = air density at the turbine location for hour j

p_j = atmospheric pressure at the turbine location from the weather file for hour j converted from atm to Pa

R_{sp} = specific gas constant for dry air (287.058 J/kg·K)

T_j = temperature from weather file for hour j converted from °C to K

The adjusted wind turbine output in W in a given hour is:

$$P_j = P(V_{h,j}) \times \frac{\rho_j}{\rho_0} \quad (28)$$

where

V_j = the wind speed at hour j from the weather file

$P(V_{h,j})$ = the turbine output at wind speed $V_{h,j}$ from the turbine's power curve (calculated in Equation 26 above)

ρ_j = the air density at hour j from the weather file

ρ_0 = the air density at sea level, 1.225 kg/m³ at 15 °C

8 Wind Farm Output from a Weather File

When you use a weather file with time series data for the wind resource data, SAM can model either a single wind turbine or a wind farm with two or more turbines.

Because SAM needs information about wind direction to calculate wake losses associated with a wind farm, it cannot model a multi-turbine wind farm when the wind resource data is defined by a Weibull distribution.

SAM makes the following simplifying assumptions about the wind farm:

- All turbines are at the same elevation above sea level so that the air density is constant across the entire wind farm.
- The terrain type is the same across the entire wind farm so that the wind shear is the same for all turbines.

When you model a wind farm with more than one turbine, SAM calculates the wind farm output for each hour using an algorithm conceptually similar to these steps:

- 1) Calculate the output and thrust coefficient of the most upwind turbine in the wind farm.
- 2) For each remaining turbine in the farm:
 - a) Determine the downwind and crosswind distance from the nearest upwind turbine using wind direction data from the weather file and turbine coordinates from the wind farm layout matrix.
 - b) Use the wake effect model to calculate the wind speed at the turbine using the output wind speed from the neighboring upwind turbine.
 - c) Calculate the turbine's electrical output and thrust coefficient at the adjusted wind speed.
- 3) Calculate the wind farm output by adding up the electrical output values of all the turbines.
- 4) Adjust the wind farm output by the wind farm loss factor.

8.1 Wind Farm Layout Matrix

In order to identify the upwind and downwind turbines in the wind farm, SAM uses a simple two-dimensional array to represent turbine locations. Each turbine location is an x,y coordinate pair that defines the distance in meters of the turbine from an arbitrary origin (0,0) where the smallest or most negative x and y values define the location of the southwest corner of a cardinally-oriented rectangle enclosing the wind farm.

The **Wind Farm** input page has a basic visual layout tool to help you specify the location of turbines using a rectangular or triangular layout. The input page also allows you to import wind turbine coordinates from a text file instead of using the layout tool. The layout tool and file format are both described in the Help topic for the Wind Farm input page [9].

In the SSC **windpower** module, you specify the rectangular coordinates of the turbine locations using two one-dimensional array variables: **wt_x** for the x-axis and **wt_y** for the y-axis location, where **wt_x = 0** and **wt_y = 0** is the origin as defined above, with distance from the origin measured in meters. The wind farm layout is independent of latitude and longitude information, and does not check for reasonability with respect to bodies of water, etc.

8.2 Wake Effect Losses

SAM provides three options for modeling wake effect losses in a wind farm. Each option uses a turbulence coefficient value as input to calculate losses due to disturbance of the wind flow to downwind turbines by neighboring upwind turbines.

The **Wake Model** variable (`wake_model` in the SSC `windpower` module) on the **Wind Farm** input page determines what wake effect model SAM uses. Table 1 summarizes the three wake effect model options, described in more detail below.

Table 6. Wake Effect Model Options in SAM User Interface and SSC Windpower Module

Wake Model (SAM)	wake_model (SSC)	Description
Simple Wake Model	0	Uses wind speed deficit calculation
Park (WAsP)	1	Implementation of approach used for WAsP software
Eddy Viscosity	2	Represents wake profile as a Gaussian curve

The Simple Wake Model is an implementation of a model developed at NREL and adapted for SAM. Park (WAsP) and Eddy Viscosity models are described briefly below with references to documents that describe them in more detail. The Simple Wake Model is suitable for most analyses in SAM. The Park (WAsP) and Eddy Viscosity wake effect models are provided to allow for comparison with implementations in other software.

8.2.1 Turbine Output and Thrust Coefficient

SAM calculates the turbine output from the turbine power curve as described in Chapters 6 and 7.

The turbine thrust coefficient characterizes the thrust, or force on the turbine rotor. SAM uses a numerical solution of the relationship between the thrust coefficient and the power coefficient to calculate the thrust coefficient.

The theoretical power in the wind depends on density, wind speed, and rotor diameter:

$$P = \frac{1}{2} \rho \left(\frac{\pi D^2}{4} \right) V^3 \quad (29)$$

where

P = theoretical power in the wind in W

ρ = air density in kg/m^3

D = rotor diameter in m

V = wind speed in m/s

The power coefficient C_p is then:

$$C_p = \frac{P(V)}{P} \quad (30)$$

where

$P(V)$ = Power at wind speed V determined from the power curve

As shown in [6], the power coefficient C_p and the thrust coefficient C_T are given by:

$$C_p = 4a(1 - a)^2 \quad (31)$$

$$C_T = 4a(1 - a) \quad (32)$$

where

a = axial induction factor (describing the wind speed drop across a turbine), which is unknown.

Solving numerically for C_T in terms of C_p gives the following relationship when $0 < C_p < 0.6$ (which is a sufficient range, since the Betz limit tells us that $C_p < 0.59$) [6]:

$$C_T = -A + BC_p + CC_p^2 + DC_p^3 \quad (33)$$

where

$$A = -0.01453989$$

$$B = 1.473506$$

$$C = -2.330823$$

$$D = 3.885123$$

8.2.2 Simple Wake Model

The Simple Wake Model [8, Chapter 3] is an adaptation of a model developed in 1996 at the University of Wisconsin's Solar Energy Research Center for the TRNSYS [11] simulation platform. The model uses the wind speed deficit factor to estimate the reduction in wind speed at a downwind turbine due to the wake of an upwind turbine.

The turbulence intensity σ is:

$$\sigma = \sqrt{\left[\frac{C_T}{7} \times \left(1 - \frac{2}{5} \times \log(2 \times x)\right)\right]^2 + C_t^2} \quad (34)$$

where

C_T = turbine thrust coefficient

x = crosswind distance between turbines in rotor radii

C_t = wind turbulence coefficient, **Turbulence Coefficient** on the **Wind Farm** inputs page, **turbul** in the SSC **windpower** module

The wind speed deficit factor f_{wsd} is:

$$f_{wsd} = \frac{C_T}{4 \times \sigma^2 \times x^2} e^{\left(-\frac{r^2}{2 \times \sigma^2 \times x^2}\right)} \quad (35)$$

where

C_T = turbine power coefficient

σ = transverse turbulence intensity (Equation 37)

x = downwind distance between turbines in number of rotor radii

r = crosswind distance between turbines in number of rotor radii

The adjusted wind speed V_{adj} is then:

$$V_{adj} = V \times (1 - f_{wsd}) \quad (36)$$

where

V = wind speed at neighboring upwind turbine

f_{wsd} = wind speed deficit factor (Equation 40)

8.2.3 Park Wake Model

The Park wake model [12] assumes that a decrease in free-stream wind speed occurs immediately behind the turbine, and that the turbine wake expands linearly downstream of the turbine, with the magnitude of this expansion given by an empirically determined wake-decay constant k . Given the geometry shown in Figure 2:

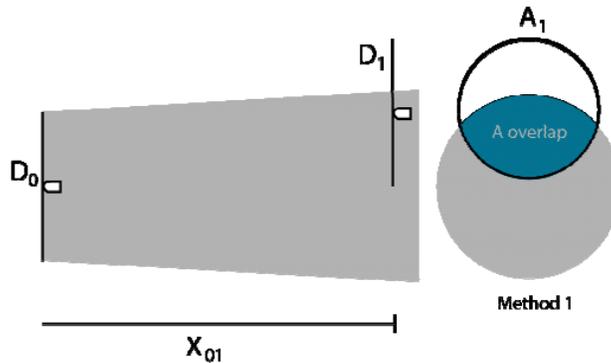


Figure 2. Geometry of the Park Wake Model

The radius r_w of the wake at the location of turbine l is computed using the wake-decay constant:

$$r_w = \frac{D_0}{2} + kX_{01} \quad (37)$$

where

D_0 = rotor diameter of the upstream turbine

k = wake-decay constant (in SAM, this is equal to 0.07, a typical value for this constant)

X_{01} = horizontal distance between the upstream and downstream turbines

$A_{overlap}$ is then computed geometrically. The decrease in wind speed occurring at the downstream turbine is then given by the wind speed deficit, calculated in the following:

$$\delta V = (1 - \sqrt{1 - C_T}) \left(\frac{D_0}{D_0 + 2kX_{01}} \right)^2 \frac{A_{overlap}}{A_1} \quad (38)$$

where

δV = wind speed deficit at the downstream turbine

C_T = thrust coefficient

$A_{overlap}$ = area of the overlap between the wake and the rotor swept area of the downwind turbine as shown in Figure 2

A_1 = the swept area of the downstream turbine's rotor

The adjusted wind speed V_{adj} at the downwind turbine is then:

$$V_{adj} = V \times (1 - \delta V_{ds}) \quad (39)$$

where

V = wind speed at neighboring upwind turbine

f_{wsd} = wind speed deficit factor (Equation 40)

In the case where a turbine is affected by more than one upstream turbine, the Park model calculates the adjusted wind speed for each upstream turbine, and uses the minimum adjusted wind speed value (i.e. the largest wake effect).

8.2.4 Eddy-Viscosity Wake Model

The Eddy-Viscosity wake model is an implementation of the numerical solution developed and described in 1996 at Renewable Energy Systems, Ltd. It implements a solution of the Navier-Stokes and continuity equations from fluid mechanics to predict the centerline velocity deficit downstream of a turbine, which is then used to represent the initial wake profile behind a turbine as a Gaussian curve. A detailed description of this model is beyond the scope of this manual, see [13] for its documentation.

This model calculates the adjusted wind speed V_{adj} of each downwind turbine in the farm based on the wind speed at the nearest upwind turbine.

9 System Electrical Output and Capacity Factor

SAM models different kinds of renewable energy systems. For each kind of system, it calculates the system's electrical output and reports it as hourly, monthly, and annual energy on the Results page. For the wind performance model, the system electrical output is the wind farm's electrical output (in some cases, the output of a single turbine). In SAM, the system's electrical output (**Annual Energy**) is the wind farm output adjusted by optional performance adjustment factors.

9.1 Hourly Output from a Weather File

For simulations that use an hourly weather file as input, SAM calculates the output of each turbine in the farm as described in Chapter 8. The wind farm's hourly electrical output is the sum of all of the turbines' electrical output, adjusted by the wind farm loss factor:

$$P_{wf,j} = \frac{L}{100\%} \times \sum_{n=1}^N P_{j,n} \quad (40)$$

where

$P_{wf,j}$ = electrical output of wind farm in hour j in kWh/h, in the SSC **windpower** module, **farmpwr**. (This value is not displayed on SAM's Results page.)

L = loss factor, **Wind Farm Losses** on the **Wind Farm** input page, **lossp** in the SSC **windpower** module

$P_{j,n}$ = electrical output of turbine n in hour j in kWh/h

N = number of turbines in the wind farm

The wind farm loss factor is intended to account for wiring and other losses associated with the wind farm design. You can account for operational losses such as system availability, curtailment, and degradation using the adjustment factors described in Section 9.3.

9.2 Annual Output Energy from a Weibull Distribution

For simulations based on a Weibull distribution of wind speed, SAM calculates each wind speed bin's contribution to the annual electrical energy output of a single turbine as described in Chapter 6. For a wind farm consisting of a single wind turbine, the annual electrical output is then:

$$Q_{wf} = \sum_{i=1}^N P_i \quad (41)$$

where

Q_{wf} = annual output of a single turbine in kWh

P_i = power output of the wind speed bin as shown in Equation 24 in kW

N = number of wind speed bins in the Weibull distribution

Recall that P_i is already adjusted by the number of hours that it occurs per year, as shown in Equation 24.

Because SAM's financial models require hourly electrical output values, SAM calculates the values by dividing the annual electrical output by the number of hours in one year:

$$P_{wf,j} = \frac{Q_{wf}}{8760} \quad (42)$$

where

$P_{wf,j}$ = electrical output of the turbine in hour j in kWh/h

Q_{wf} = annual output of a single turbine

8760 = number of hours in a year

9.3 Performance-Adjusted System Output

SAM applies a set of adjustment factors to the performance model's results to account for operational losses due to maintenance downtimes, grid operator curtailment requirements, or annual output degradation due to aging of system components. These factors are inputs on the **Performance Adjustment** input page. In SSC, these adjustment factors are not part of the **windpower** module. They are in the **annualoutput** module, and can use **windpower** module outputs as inputs.

The performance adjustment factors are (see [14] for more details):

- The **Percent of annual output** factor (**energy_availability** in the SSC **annualoutput** module) is applied to the wind farm (or turbine) annual output.
- The **Year-to-year decline in output** factor (**energy_degradation** in SSC) is applied to the annual output in Years 2 and later of the project cash flow.
- The **Hourly Factors** (**energy_curtailment** in SSC) are applied to the hourly output.

SAM reports the hourly, monthly, and annual energy values in results both before and after the performance adjustment factors.

9.4 System Annual Electrical Output (Annual Energy)

The system's annual electrical output is the sum of the turbines' output adjusted by the performance adjustment factors described in Section 13.3. SAM reports this value on the Results page as **Annual Energy**:

$$Q_{sys} = \sum_{n=1}^{8760} (P_{wf,j} \times F_{adj,j}) \quad (43)$$

where

Q_{sys} = adjusted annual electrical energy output of the system in kWh. (In SSC, this value can be calculated using the **annualoutput** module.)

$P_{wf,j}$ = electrical output of wind farm in hour j in kWh/h, in the SSC **windpower** module, **farmpwr**

$F_{adj,j}$ = hourly adjustment factor defined on the **Performance Adjustment** input page in SAM, and in the SSC **annualoutput** module

9.5 Capacity Factor

The system's capacity factor is the ratio of the system's annual electrical output to its potential output at the wind farm's rated capacity:

$$K = \frac{Q_{sys}}{P_m \times 8760} \quad (44)$$

where

K = system capacity factor

Q = system's total annual electrical output in kWh after performance adjustments

P_m = wind farm's rated capacity in kW, **System Nameplate Capacity** on the **Wind Farm** input page

8760 = number of hours in one year

10 Summary

The wind power model described in this manual is an hourly simulation model developed and distributed by the National Renewable Energy Laboratory that calculates a wind power system's hourly electrical output. The model is available for project modelers as part of the System

Advisor Model, and for software developers as the **windpower** module in the SAM Simulation Core software development kit. The model can simulate the performance of a single wind turbine or wind farm using weather data from a weather file or specified as a Weibull distribution. The model uses a wind turbine power curve to calculate the electrical output of a single turbine. For simulations of a wind farm, the model adjusts the output of each turbine in the farm using a wake effect model. A set of performance adjustment factors account for project operating losses.

11 Index of SAM and SSC Variable Names

This index lists the page numbers where SAM and SSC variables are discussed in this manual. See Table 1 for a list of variable names used in the equations in the chapters above.

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