User Guide

Wind Turbine Economic Assessment Tool (WiTEAT)

Full Version 1.0.1

Author: Dr Yakubu Abdul-Salam
Applied Economist and Research Fellow
The James Hutton Institute, Aberdeen, UK

Email: yaksamash@hotmail.com; yakubu.abdul-salam@hutton.ac.uk
Tel: +44 (0) 777 420 4358; +44 (0) 1224 595453
Available at www.energybusinesseconomics.com

1 The wind power model underlying WiTEAT

For most locations, accurate modelling of the energy output (kWh) of a wind turbine is challenging due to variabilities in wind speed and turbine technology designs. The Wind Turbine Economic Assessment Tool (WiTEAT) presented here is based on a model introduced by Deichmann et al (2011). Given location-specific and turbine technology parameters, this model calculates the expected energy output of a wind turbine. The model is especially detailed in its incorporation of the wind turbine technology parameters known to influence efficiency of energy conversion and output, hence its adoption for implementation in WiTEAT.

Deichmann et al (2011) illustrate the calculations underlying their model by using an example of a 1 kW wind turbine at a given location, showing the conversion of wind speed (m/s) to energy output (kWh) for this location. Below we repeat their illustration by adopting the parameter values used in their example. WiTEAT is written so that users can provide values for all the parameters mentioned below, and at the click of the execute button, results are produced based on the model calculations shown in the example.

1.1 Definition of the input parameters and output variables in the wind power model underlying WiTEAT

Table 1 below shows the definitions of the input parameters and output variables in the Deichmann et al (2011) wind power model that underlies WiTEAT.

Input parameters	**Description**
Site Altitude	The project site elevation (m) above sea level.
Anemometer Height	The height (m) above sea level at which the average wind speed at the project site is measured.
Mean Wind speed	The average annual wind speed (m/s) at the anemometer height.
Weibull k	The probability distribution of wind speed where k is the shape factor. Values of k ranging from $k=1.8$ to $k=2.3$ usually fit the distribution well. Often the Rayleigh distribution which is a special case of the Weibull distribution at $k=2$ is used to approximate the wind distribution for inland sites. Deichmann et al. (2011) recommend the use of $k=3$ for coastal sites as a first approximation.
Wind Shear Exponent	A dimensionless number denoting the rate at which wind speed varies with the height above sea level. Lower values of the shear exponent (i.e. 0.10-0.13) denote a smooth terrain which typically is associated with offshore sites. A higher exponent of the shear exponent (i.e. 0.25-0.40) denotes a rough terrain which typically is associated with urban sites. These have sizable obstacles (e.g. buildings, trees) in the path of wind. The shear exponent values range between 0.10-0.40 and a value of 0.14 is recommended when approximating site characteristics.
Tower Height	The hub height of the turbine (m).
Hub Height	The height of the turbine's hub (m).
Turbulence Factor	Inefficiencies undermine the manufacturer rating of a wind turbine. A key source for these inefficiencies is the turbulence factor of the wind at the project site. Deichmann et al. (2011) recommend the use of a turbulence factor of 0.1 (10%) - 0.15 (15%) in most cases. Using a factor of 0% tends to over-predict performance of a turbine.
Output variables	
Hub Mean Wind Speed	Extrapolated wind speed at the height of the turbine hub (m/s)
Air Density Factor	Air Density Factor is a ratio of the density of air at a given altitude to the density of air at standard temperature and pressure. Like the turbulence factor, the density of air contributes to the efficiency of the turbine.
Average Output Power	The average continuous equivalent power of the turbine (kW)
Daily Energy Output	Average energy produced per day (kWh)
Annual and Monthly Energy Output	Calculated using the daily value (kWh)
Percent Operating Time	Percent of the time in a year that the turbine generates some power (%)

Table 1: Input parameters and output variables in the Deichmann et al (2011) wind power model underlying WiTEAT (Source: Deichmann et al.,2011)

1.2 Example calculation of power and energy output in the wind power model underlying WiTEAT

For their illustration, Deichmann et al (2011) use the input parameter levels shown in Table 2 below. Table 2 also shows the immediate input-output relationships of these parameters. The red-marked outputs in Column 4 of Table 2 are determined in Table 3.

Inputs		**Outputs**		**Calculations**
A - Site Altitude (m)	2000	H - Hub Mean Wind Speed (m/s)	6.66	$H = C * (F/B)^E$
B - Anemometer Height (m)	50	I - Air Density Factor	-0.18	$I = -0.18$
C - Mean Wind Speed (m/s)	7.89	J - Average Output Power (kW)	**0.2957**	
D - Weibull k	2	K - Daily Energy Output (kWh)	7.096	$K = J * 24$
E - Wind Shear Exponent	0.14	L - Annual Energy Output (kWh)	2590.04	$L = K * 365$
F - Tower Height (m)	15	M - Monthly Energy Output (kWh)	215.84	$M = L / 12$
G - Turbulence Factor	0.10	N - Percent Operating Time (%)	**89.52**	

Table 2: Part 1 of calculations in the Deichmann et al (2011) wind power model underlying WiTEAT (Source: Deichmann et al.,2011)

Table 3 below summarises the further computations required to arrive at the estimated wind power output of 0.2957 kW (highlighted in red in Table 2 above) and the percent operating time of the turbine (also highlighted in red in Table 2 above). Column 1 of Table 3 is a grid of the possible wind speeds at the site where the wind turbine is installed. Column 2 is known as the wind turbine power curve and is provided by manufacturers of wind turbines. It indicates the instantaneous generated power associated with each element of the wind speed grid in Column 1 under standard conditions of temperature and pressure. For the current illustration, Deichmann et al. (2011) state that the cited power curve in Column 2 is that of an SW Whisper H40 wind turbine. Column 3 is the corrected instantaneous power generated by the wind turbine under site-specific conditions. Part of the reasons for the correction is the inefficiencies generated by wind turbulence and air density at the site. For each row in Column 2, the corresponding row in Column 3 is computed as follows;

$$[\text{Column 3}] = [\text{Column 2}] \times (1 - G) \times (1 + I) \tag{1.1}$$

Column 4 is the probability of the event of a wind category in Column 1. This is computed using the Weibull formula. For each row of Column 1, the corresponding row in Column 4 is computed as follows;

$$\begin{aligned}[\text{Column 4}] = {} & \left(D / (1.123 \times H)\right) \times \left([\text{Column 1}] / (1.123 \times H)\right) \wedge (D - 1) \\ & \times exp\left(-\left(\left([\text{Column 1}] / (1.123 \times H)\right) \wedge D\right)\right)\end{aligned} \tag{1.2}$$

The sum of all probabilities in Column 4 is N, the percent Operating Time and is calculated to be 0.8952. Finally the expected output (kW) for each wind category (m/s) in Column 1, given the site-specific parameters, is computed in Column 5. For each row of column 3 and column 4, the corresponding cell in column 5 is computed as follows;

$$[\text{Column 5}] = [\text{Column 3}] \times [\text{Column 4}] \tag{1.3}$$

The sum of all expected wind outputs in Column 5 gives the expected power output of the wind turbine. In the present example, this is calculated to be 0.2957kW. Based on this calculation the expected daily, monthly and annual energy output of the wind turbine can be calculated as 7.096kWh, 215.84kWh and 2590.04kWh respectively, as shown in Table 2.

Column 1 Wind speed (m/s)	Column 2 Power (kW)	Column 3 Corrected power (kW)	Column 4 Wind Probability (Φu)	Column 5 net kW@v
0	0	0.000	0.0000	0.00000
1	0	0.000	0.0351	0.00000
2	0	0.000	0.0665	0.00000
3	0	0.000	0.0912	0.00000
4	0.062	0.046	0.1074	0.00491
5	0.123	0.091	0.1143	0.01037
6	0.233	0.172	0.1127	0.01937
7	0.376	0.277	0.1042	0.02892
8	0.540	0.399	0.0911	0.03631
9	0.700	0.517	0.0757	0.03909
10	0.891	0.658	0.0599	0.03938
11	1.064	0.785	0.0453	0.03555
12	1.208	0.892	0.0328	0.02920
13	1.240	0.915	0.0227	0.02078
14	1.202	0.887	0.0151	0.01339
15	1.149	0.848	0.0096	0.00817
16	1.099	0.811	0.0059	0.00479
17	1.047	0.773	0.0035	0.00269
18	0.993	0.733	0.0020	0.00145
19	0.941	0.694	0.0011	0.00075
20	0.895	0.661	0.0006	0.00037
21	0.848	0.626	0.0003	0.00018
		Totals	**0.8952**	**0.2957**

Table 3: Example of wind energy yield estimation in the Deichmann et al (2011) model underlying WiTEAT (Source: Deichmann et al.,2011)

1.3 Calculating decision support indicators (NPV, IRR, Breakeven prices) in WiTEAT

Having calculated the potential annual energy output of a wind turbine at a given location, as shown in Table 2 and Table 3 above, WiTEAT calculates the user specified economic decision support indicator for investment in the wind turbine at that location. Three choices of indicators are given. These are the Net Present Value (NPV), the Internal Rate of Return (IRR) and the breakeven prices for the electricity produced. Let t represent time periods (years) and let T represent the total expected lifetime of a wind turbine technology at the given location (e.g. 15 years). Also let $annualElectricityGeneration(t)$ represent the annual electricity (energy) generation of the wind turbine at the given location. In the case of the example cited in Section 1 above, the annual electricity generation of the 1kW turbine at the given example site is 2590.04kWh, as shown in Table 2. Given these figures, the NPV economic decision support indicator for example is calculated in WiTEAT as follows;

$$solve \quad NPV = -totalCapitalCost + \sum_{t=0}^{T-1} \frac{cashFlow(t)}{(1 + discountRate)^{t-1}} \tag{1.4}$$

where

$$\begin{aligned} cashFlow(t) = {} & postTaxProfit(t) + machineryDepreciationCost(t) \\ & + buildingDepreciationCost(t) \end{aligned} \tag{1.5}$$

$$postTaxProfit(t) = preTaxProfit(t) - tax(t) \tag{1.6}$$

$$tax(t) = taxRate \times preTaxProfit(t) \text{ if } preTaxProfit(t) > 0 \tag{1.7}$$

$$\begin{aligned} preTaxProfit(t) = {} & electricityRevenue(t) \\ & - overheadCost(t) - loanRepaymentCost(t) \\ & - machineryDeprecicationCost(t) \\ & - buildingDepreciationCost(t) \end{aligned} \tag{1.8}$$

$$\begin{aligned} electricityRevenue(t) = {} & ((elecPriceGenFIT + elecPriceExport)/100) \\ & \times (1 + inflationRate)^{t-1} \\ & \times annualElectricityGeneration(t) \end{aligned} \tag{1.9}$$

where

totalCapitalCost, £	Total capital cost of investment in wind turbine
cashflow(*t*), £	Cashflow in period *t*
discountRate, %	Discount rate
postTaxProfit(*t*), £	Post tax profit in period *t*
machinerDepreciationCost(*t*), £	Machinery depreciation cost in period *t*
buildingDepreciationCost(*t*), £	Building depreciation cost in period *t*
tax(*t*), £	Tax cost in period *t*
taxRate, %	Tax rate
preTaxProfit(*t*), £	Pre-tax profit in period *t*
electricityRevenue(*t*), £	Revenues from sale of electricity in period *t*
overheadCost(*t*), £	Overhead cost in period *t*.
loanRepaymentCost(*t*)	Loan repayment cost in period *t*

electricityRevenue(*t*), £	Revenue from sale of electricity in period *t*
annualElectricityGeneration(*t*), kWh	Total electricity generated in period *t*
inflationRate, %	Inflation rate
elecPriceGenFIT, p/kWh	Initial year FIT for electricity generation
elecPriceExport, p/kWh	Initial year market rate for sale of electricity

IRR and breakeven prices are similarly calculated using the capital budgeting approach shown above.

2 Other wind power models

2.1 Nguyen (2007) model

The wind probability distribution for an average wind speed V_m of a site is given by the following Rayleigh function

$$f(v) = \frac{\pi v}{2(V_m)^2} \exp\left(\frac{-\pi}{4}\right)\left(\frac{v}{V_m}\right)^2 \tag{1.10}$$

where $f(v)$ is the probability of the event of wind speed v during the year and v is a grid of wind speeds, typically 0 – 20 m/s. The delivered energy of a wind turbine is then computed by simply integrating the power curve as follows;

$$E(V_m) = \sum_{v=1}^{20} \eta f(v) P(v) \times 8760 \tag{1.11}$$

$E(V_m)$ is the total annual usable energy output; η is the efficiency and $P(v)$ is the wind turbine power curve as provided by the manufacturer.

2.2 RWE-NPOWER-UK model

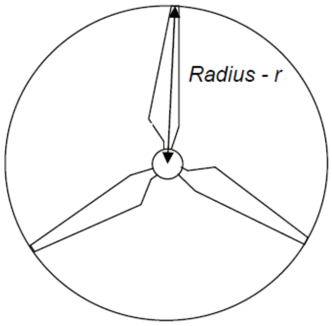
The ideal maximum power outputted by a wind turbine converting kinetic energy in wind to mechanical or electrical energy is given by the following;

$$P = \frac{1}{2}\rho A v^3 \tag{1.12}$$

where P is power (W); ρ is density (kg/m^3); A is swept area (m^2) and v is wind speed (m/s). Whilst the above equation is elegantly derived, the power P is practically unattainable by any wind turbine. Albert Betz in 1919 showed that a wind turbine can convert only up to 59.3% of the kinetic energy of wind into mechanical energy turning the blades. This bound is known as the Betz Limit. Theoretically therefore, no wind turbine of any design could attain efficiency levels above the Betz Limit. The Bertz Limit is also known as the efficiency or power coefficient C_p of a wind turbine. The power coefficient is unique to every wind turbine and is provided by manufacturers. In the real world, wind turbines typically do not have power coefficients close to the Bertz Limit. Inefficiencies sourced from the strength and durability of the wind turbine; the frictional losses encountered in the operation of its gearbox, wiring, bearings, generator heat losses and so on means that the power coefficient is much smaller than the Bertz Limit. Typically, wind turbines have power coefficients of about 0.10 – 0.30 indicating the percentage energy in the wind that is actually converted into usable electricity by the turbine. Factoring the power coefficient into the theoretically ideal derivation above gives;

$$P = \frac{1}{2}\rho A v^3 C_p \tag{1.13}$$

The sweep area A is the total area span of the blades of the turbine. For the example wind turbine in the figure below, this can be calculated using the equation of the area of a circle;



$$Sweep\ Area, A = \pi r^2$$

Acknowledgement

The text in this document is partly lifted from the author's PhD thesis, cited in 'References' below.

Reference

Abdul-Salam, Y. (2014). 'Access to electricity in sub Saharan Africa: modelling the importance and adoption of off-grid renewables' (Doctoral dissertation, University of Aberdeen).

Deichmann, U., Meisner, C., Murray, S., & Wheeler, D. (2011). 'The economics of renewable energy expansion in rural Sub-Saharan Africa.' *Energy Policy*, *39*(1), 215-227.

Nguyen, K. Q. (2007). 'Alternatives to grid extension for rural electrification: Decentralized renewable energy technologies in Vietnam.' *Energy Policy*, *35*(4), 2579-2589.