TurbSim: Reliability-based Wind Turbine Simulator

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***Abstract*—Wind turbine farms are an effective generator of electricity in windy parts of the world, with prices progressing to levels competitive with other sources. Choosing the correct turbine for a given installation requires significant engineering and the current trend leads towards groups of large horizontal axis turbines. Unfortunately, large wind turbines have to contend with large forces and other sources of failure. With the new push to move generation farms offshore where they are less accessible, the issue of reliability becomes more critical. This work investigates the impact of reliability in a life-cycle analysis simulation of a theoretical wind farm in Massachusetts based upon reliability information from a number of academic sources. The simulator, TurbSim, is designed with significant modularity to enable reliability simulation of any turbine with available wind information. Our simulation of a turbine indicated that reliability makes a small but noticeable impact of 1.24% in its output.**

I. INTRODUCTION

Wind turbine farms are commonly used to generate electricity in windy parts of the world, with prices progressing to competitive levels. In Europe countries such as Denmark and Germany, government initiatives have cause a proliferation of turbines. The wide-spread use of turbines has reduced these countries' dependence on non-renewable traditional energy sources. The United States lags in deployment of turbines, but there is a current emphasis on domestic security starting with elimination of dependence on oil. This has resulted in significant investment into large scale deployment of generation farms in the US. [1]

Large-scale horizontal-axis wind generators are generally considered to be more efficient, though such large wind turbines have large forces to contend with. GE's website [2] claims that the horizontal gearbox forces cause the most common failures, but the actual failure and performance are not easy to model. Sadly, such performance data is exceedingly difficult to acquire, though the methodology of proper simulation is well documented. [3], [4]

In addition, there is a current trend to make use of the higher potential output of offshore turbine deployment. [5] Part of this push comes from the difficulty of gaining rights to use prime areas for developing wind-farms. In Massachusetts we have had interesting political story develop regarding the Cape Wind project on Cape Cod. As more of these generation farms go offshore accessibility also becomes an issue.

With the improved reliability of modern turbines, it is believed that inaccessibility would not be an issue on generator output. Regardless, reducing the cost associated with maintenance is still active research. [6] However, a formal analysis of reliability and its impact on generator output is not to be found.

Professor Sclavonous of MIT gives an estimate of 35% for the efficiency compared to optimal performance for an average wind turbine. [5] The actual performance of a given turbine at a given location requires a significant amount of turbine performance data in addition to accurate meteorological data. Thankfully, the National Oceanic and Atmospheric Administration has been collecting such information for the US. [7]

The focus of our research will be on what proposed changes will do for generation efficiency via reduction of downtime. We will take these results and apply them to concepts of Life Cycle Analysis(LCA) to determine the Energy Return on Investment (ERoI). A critical component for this simulation is a detailed reliability model of the wind turbine which will be based upon results in [8].

II. SCOPE OF WORK

Here we address how this change in efficiency impacts life cycle analysis of horizontal wind turbines[1]. A common question asked is, "What is the Return on Energy Investment for a Turbine?" To complete such an analysis requires knowing the amount of energy required to build, operate, and dispose of a turbine. [9]

The theoretical physical limit for a turbine's efficiency based upon fluid flow models is 58%. Building such a turbine would be impractical due to the physical limits of the current wind-foil technology [4]. Professor Paul Sclavonous gives an estimate of 35% for the efficiency as a much more typical number [5]. This work refines that number by giving estimates of reliability degradation.

III. TURBSIM: SIMULATOR OF REALISTIC TURBINES

In [6], the challenge of estimating changes to a wind turbine in terms of its reliability and performance are discussed. Previous simulators that are freely available such as [10], assume that a wind turbine is always functioning. TurbSim, which was developed for this project, includes the factor of downtime and repair in its calculations. We chose the Vestas V90-2MW generator, as there is a reasonable amount of literature available.

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[1] Which we will refer to as turbines for the rest of the paper.

A. *Turbine*

A turbine is defined at an abstract level as a box. At a given wind-speed a given amount of power comes out. This is the basic model used in most turbine simulation systems and is an empirically verified power curve supplied by a turbine manufacturer.

Combs [1] from [11] notes that the general formula for calculating a wind turbine's power is:

$$p = 0.5 \rho A C_p V^3 N_g N_b \tag{1}$$

Where

p : power (W)
ρ : air density (kg/m^3)
A : rotor swept area (m)
C_p : Coefficient of performance
V : wind speed (m/s)
N_g : generator efficiency
N_b : gearbox/bearings efficiency

Our model adds an additional factor by considering the loss of generation when a turbine breaks down.

B. *Reliability*

Our focus is on what the inclusion of unreliable elements will do for generation efficiency and furthermore the life cycle analysis. A critical component for this simulation is a detailed reliability model of the wind turbine which is based upon data from [8], [12], [13].

Tavner *et al.* [8] gives an excellent summary of Danish and Wind Turbine failures based upon WindStats, in particular the Mean Time Between Failure(MTBF) as shown in Table I. The model used is:

$$\lambda(t) = \frac{\beta}{\Theta} \left(\frac{t}{\Theta} \right)^{\beta - 1} \tag{2}$$

t: time
β: a parameter that allows us to tune the function according to what part of the "bathtub" curve it is in.
Θ : is the intensity function.
λ : is failure probability

Valid values for β are:

- Early Failure: $\beta < 1$
- Constant Failure: $\beta = 1$. This is equivalent to a homogeneous Poisson process.
- End of Life Deterioration: $\beta > 1$

Unfortunately, we cannot use the Power Law process for lack of sufficient data to characterize the power law curve under our conditions. So we only use the MTBF subsystem statistics.

Hahn *et al.* [13] gives summary statistics on the Mean Time To Repair(MTTR) for German turbines as shown in Table II. Making adjustments for terminology, we were able to build a Poisson-process simulator for an individual wind turbine.

TABLE I
MTBF FOR GERMAN AND DANISH TURBINES FROM HPP MODEL IN [8]

Subassembly	German MTBF(h)	Danish MTBF(h)
Rotor blades	39,297	252,033
Air brake	180,078	1,286,050
Mechanical Brake	223,447	627,055
Main shaft	365,339	807,174
Gearbox	87,174	218,871
Generator	73,234	365,534
Yaw system	69,504	318,903
Electrical controls	39,205	175,561
Hydraulics	79,363	285,195
Grid or Electrical system	25,708	450,643
Mechanical or pitch control system	90,472	1,236,712
Other	25,449	51,871

TABLE II
GERMAN WIND TURBINE MTTR FROM [12]

Component	MTTR(h)
Rotor blades	96
Air brake	72
Mechanical brake	96
Main Shaft	132
Gearbox	150
Generator	174
Yaw system	60
Electrical controls	46
Hydraulics	24
Grid or electrical system	36
Mechanical or pitch control system	60
Sensors	36
Rotor hub	84
Supporting Structure/Housing	72
Other	48

The TurbSim system creates a Perl object for each turbine with an entry for each subsystem. Upon initialization, the turbine uses the Poisson probability distribution function to choose times for when that subsystem will break. Upon entering a time that has a broken component, the MTTR parameters are used to generate a time for it to be repaired. In addition, the output of the turbine is set to a degraded mode depending upon the effect of the broken subsystem ($d_i < 1$). So for each system:

$$k_i = \begin{cases} 1 & \text{if subsystem is functioning,} \\ d_i & \text{if subsystem is broken.} \end{cases} \tag{3}$$

To determine the degraded output (P') of a turbine compared to the full output (P), we consider the combined effects of Equation 3 on the system.

$$P' = P * \prod_i k_i \tag{4}$$

At the end of the repair interval, the degradation from that component is removed, and the next time at which it will break is regenerated.

This design was chosen to allow for easy modification of MTTR and MTBF parameters, enabling various what-if simulations for replacing components or processes. A future model would make use of [12]'s bathtub-curve model to simulate the changes in reliability of each component.

C. Wind

The other major element in a simulation is accurate wind data. This is usually accomplished with a Weibull model based on wind surveys. Perl was chosen as the appropriate wind survey parser language for wind information due to its highly optimized text processing capabilities.

A Weibull model is based upon the probability distribution function:

$$Q = 1 - e^{-(\frac{x}{\beta})^{\alpha}} \tag{5}$$

Where

x	is the random variable
Q	is the output (our wind-speed)
α, β	are constants that shape the PDF

Solving Equation 5 for x

$$x = \beta(-\ln(1-Q))^{\frac{1}{\alpha}} \tag{6}$$

We use Equation 6 to convert from a standard random number generator into a Weibull random number generator.

Combs [1] from [14] described the logarithmic profile of terrain on wind-speed:

$$v_2 = v_1 \left(\frac{\ln(h_2/z_0)}{\ln(h_1/z_0)} \right) \tag{7}$$

Where

v_2	wind velocity at height of turbine (m/s)
v_1	wind velocity at height of 10 m (m/s)
h_1	height for which the measurement of site selection (usually corrected to 10m)
h_2	turbine hub height
z_0	roughness of terrain (m)

We apply the Equation 7 as a correction factor to the output of Equation 6 to get a simulated wind-speed at a given height. This is also used when the wind-speed is known at a given height to allow simulation of turbines at different heights.

For our final simulation, we have downloaded data from the NOAA website and analyzed it for promising sites based upon average wind-speed. This data was then parsed and used as inputs for the turbine module to simulate a theoretical turbine at that location. It is common practice to use 10 years of data when attempting to predict a given wind turbines performance at a future time. This is less relevant, as our study is comparing the difference between perfect performance at a given speed compared to what the power output of when the factor of reliability is included. For this initial study, we simulated a single year's worth of data and repeated it over the life of the turbine.

In the absence of an easily available survey for the Boston area, we chose to use the NOAA's weather station data for the WQS station in the Blue Hills, adjusted for the change in height according to a logarithmic profile model as shown in Equation 8. $U(z)$ is the wind velocity at height z, U^* is friction velocity, k is von Karman's constant (0.4), and z_0 is the surface roughness length, a characterization of the ground terrain.

TABLE III
V90 Estimated Bill of Materials, based upon [9]

	ton	kg	kWh
Steel	416.08	377461.42	4745466
Glass Fiber Composite	21.25	19276.03	111331
Copper	3.40	3084.43	95698
Cast Iron	8.50	7711.07	70034
Concrete	1080.00	979759.00	979760
Aluminum	0.77	694.00	39053
Total	1529.99	1387986.46	6041320

$$U(z) = \frac{U^*}{k} \ln\left(\frac{z}{z_0}\right) \tag{8}$$

Applying Equation 9 to two different heights allows us to estimate $U(z)$ at a desired height based upon the measured speed at a reference height z_r. [4]

$$U(z) = U(z_r)\left(\frac{\ln\frac{z}{z_0}}{\ln\frac{z_r}{z_0}}\right) \tag{9}$$

D. Power Curve

The power curve for the V90 is only freely available in document form. Attempts to get updated performance specifications from Vestas did not receive a reply.

To approximate the power curve from the available document, we traced the curve on graph paper and interpolated values. Optimally, we would get base power curve information from the manufacturer, unfortunately, such information is difficult to obtain. The power curve that was derived was examined against the V80-2MW generator's table matching wind-speed to output and determined to be sufficient. A lot of computational effort goes into calculating the output, so previously determined values are memoized to increase performance.

E. Life Cycle Analysis

Since our end-goal is to complete a life-cycle analysis with this updated information, we chose to focus on the Vesta V90-2MW generator which is also used in [9]. In addition, we have processed the data using the GREET model originally developed at Argonne National Laboratory for detailed life cycle analysis of vehicles. [10]

Using these methods produces a number of different values for the total energy cost for the creation and use of V90 turbine. Using the GREET method gives an estimate of 21744 GJ for the 1530 ton unit. Nalukowe *et al.* used SimaPro to calculate 28062 GJ. From past experience with LCA, such differences are not surprising. The defined boundary of an LCA and the material energy cost information vary significantly depending upon the source.

TABLE VI
TURBSIM V90 LCA ENERGY RETURN ON INVESTMENT

	Period	GREET	Nalukowe, *et al.*
Normal	Life	0.05	0.07
	Year	1.04	1.35
	Month	12.53	16.17
Offshore	Life	0.05	0.07
	Year	1.06	1.36
	Month	12.68	16.36

IV. RESULTS

The simulation base results break down to three base statistics:

Perf: assumes the turbine runs at full capacity for the entire duration.

Max: assumes that the turbine follows the given power curve for the wind parameter, but never breaks down.

Sim: the realistic turbine that occasionally breaks and is repaired.

In addition, there are derived statistics:

ν: (efficiency) simulated output divided by Perfect output.

WL: (Wind Loss) energy lost from non-ideal wind conditions; Maximum subtracted from Perfect.

BL: (Breakdown Loss) energy lost from non-functional (or degraded) internal turbine operation; Simulated subtracted from Maximum and compared to Maximum as a ratio.

The these statistics are shown in Table IV. Interestingly enough, the ratio of $\frac{BL}{\text{Max}}$ is 1.24%. This agrees with [12] which states modern turbine reliability at 98%.

Additionally, we have considered the proposed off-site turbine deployment by doubling the MTTR as shown in Table V. This has resulted in a doubling in the mean loss of efficiency and quadrupling of the standard deviation.

For our Energy Return on Investment(ERoI), we compare this lifetime energy generation to the energy required to manufacture and operate the turbine(Table VI). Even including the effect of reliability, a V90 turbine pays for itself energy-wise in a little over a year. The ERoI is not significantly affected by the offshore MTTR adjustment.

V. CONCLUSION

Our analysis and simulation of a Vesta V90 wind turbine determined that reliability makes a small but noticeable impact (1.24%) on its power generation output. Another simulation of an off-site generator indicated an impact of 2.38% on expected output. Though these losses do not heavily increase the Energy Return on Investment (ERoI) which is between 12 and 16 months, it does represent a significant loss of energy generation over the lifetime of the turbine – 1.45E6 to 2.79E6 GJ. TurbSim should enable turbine manufacturers and wind-farm operators to make reasonable estimations for the loss associated with downtime.

VI. FURTHER WORK

Having access to a general purpose wind turbine simulator opens up a number of venues for future research.

- Examine the effect of proposed modifications to wind turbine design on reliability.
- Refine failure bathtub curves and apply them to the model.
- Compare estimated reliability impact to empirical statistics (when available).
- Include additional factors for repair resource availability including manpower and spare parts.
- Complete cost-basis justification for correct maintenance schedule and reserved resources.

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WIND REFERENCE INFORMATION

Roughness

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TABLE IV
TurbSim V90 Results for 20 year simulation

	Perf	Max	Sim	ν	WL	BL	
	GJ	*GJ*	*GJ*	%	*GJ*	*GJ*	%
mean	3.51E8	1.17E8	1.16E8	33.4	2.34E8	1.46E6	1.24
std. dev.	0	0	174117	0.05	8.58E-8	174117	0.15

TABLE V
TurbSim V90 Results for 20 year offshore simulation

	Perf	Max	Sim	ν	WL	BL	
	GJ	*GJ*	*GJ*	%	*GJ*	*GJ*	%
mean	3.51E8	1.17E8	1.14E8	33.4	2.34E8	2.79E6	2.38
std. dev.	0	0	420650.9	0.12	8.58E-8	420650.9	0.36

TABLE VII
Roughness Classes and Lengths [1]

Roughness Class	Roughness Length (m)	Energy Index (%)	Landscape Type
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 1250 meters.
2	0.1	39	Agricultural land with some houses and 8 meters tall sheltering hedgerows with a distance of approx. 500 meters.
2.5	0.2	31	Agricultural land with some houses and 8 meters tall sheltering hedgerows with a distance of approx. 250 meters.
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	18	Larger cities with tall buildings
4	1.6	13	Very large cities with tall buildings and skyscrapers