Stochastic modeling of Wind Speed

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December 2007

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Contents

1 INTRODUCTION

This paper deals with the problem to, based on measurements, at an appropriate manner analyse some available wind speed data regarding relevant input parameters for a specific stochastic wind speed model. The present wind speed model is developed as a subsystem to the complete simulation model according to reference [1].

The wind speed data is collected during 4 periods according to:

1)	27 – 29	May 2007	(72 hours)
2)	2 – 4	June 2007	(72 hours)
3)	9 – 11	June 2007	(72 hours)
4)	17 – 21	June 2007	(120 hours)

The measurements were realized at Chalmers wind power system at Hönö. The measurement point was about 20 m over the sea level.

Each period is analysed separately in respect of the model parameters.

2 MEASUREMENT RESULTS

The measurement results from the 4 periods in question (see chapter 1) are illustrated in Figure 1 to Figure 8. The wind speed data is presented as mean values during sampling intervals of 1 minute respectively 1 hour. As can be seen there is a significant difference depending on which sampling period that is used. If a sampling period of 1 hour is in question, then the turbulence contributions are effectively eliminated. On the other hand if 1 minute is used as sampling period these “high frequency” contributions are important parts of the result. The dividing into so called “low frequency” respectively “high frequency” contributions is used in the present wind speed model. See chapter 3. The measurements were taken from [2].

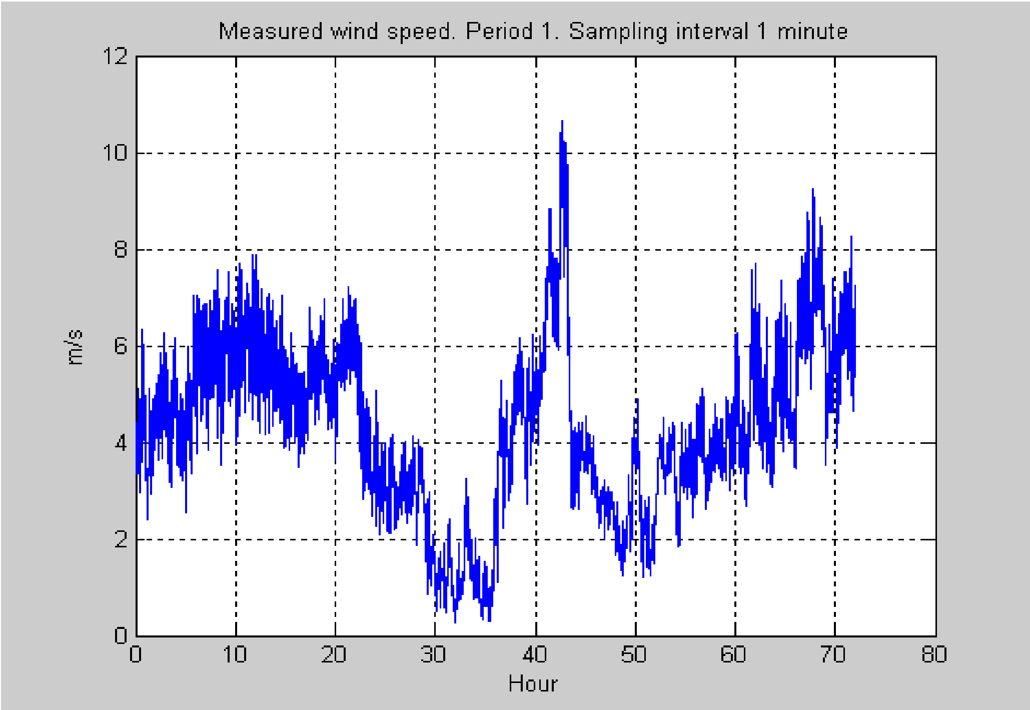

Figure 1 Measured wind speed. Period 1.
Mean value during a sampling period of 1 minute

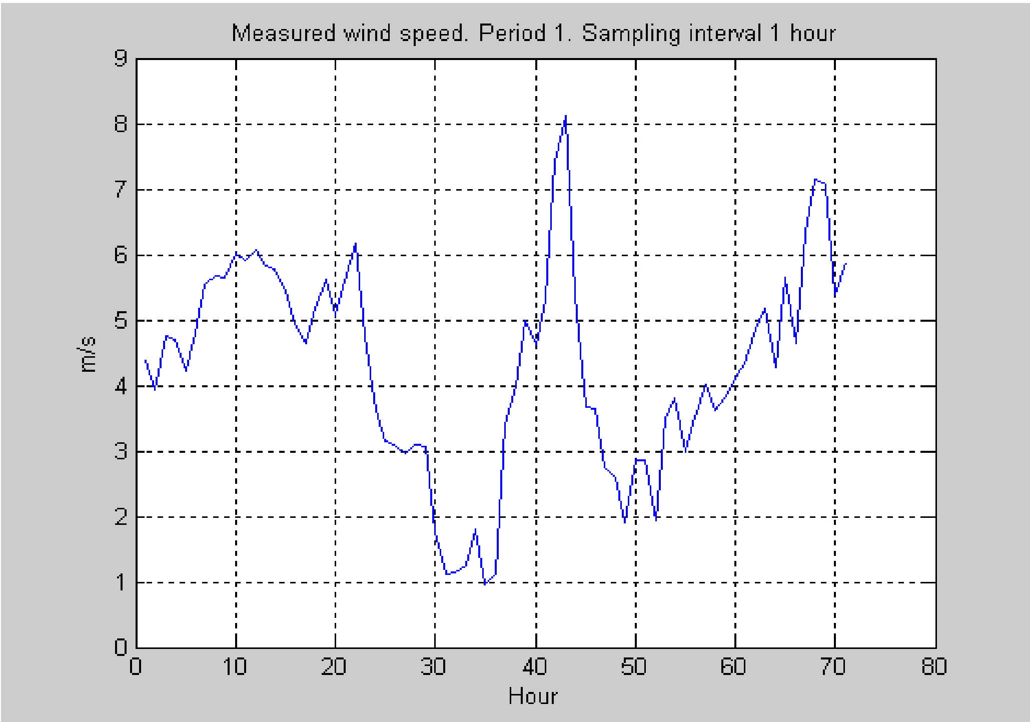

Figure 2 Measured wind speed. Period 1.
Mean value during a sampling period of 1 hour

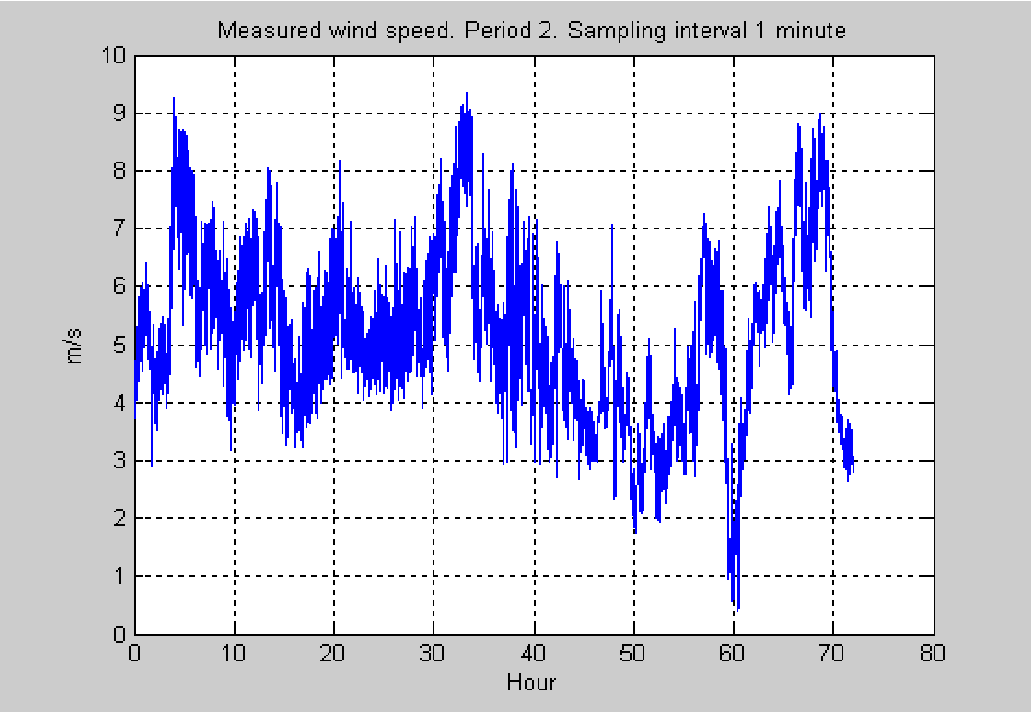

Figure 3 Measured wind speed. Period 2.
Mean value during a sampling period of 1 minute

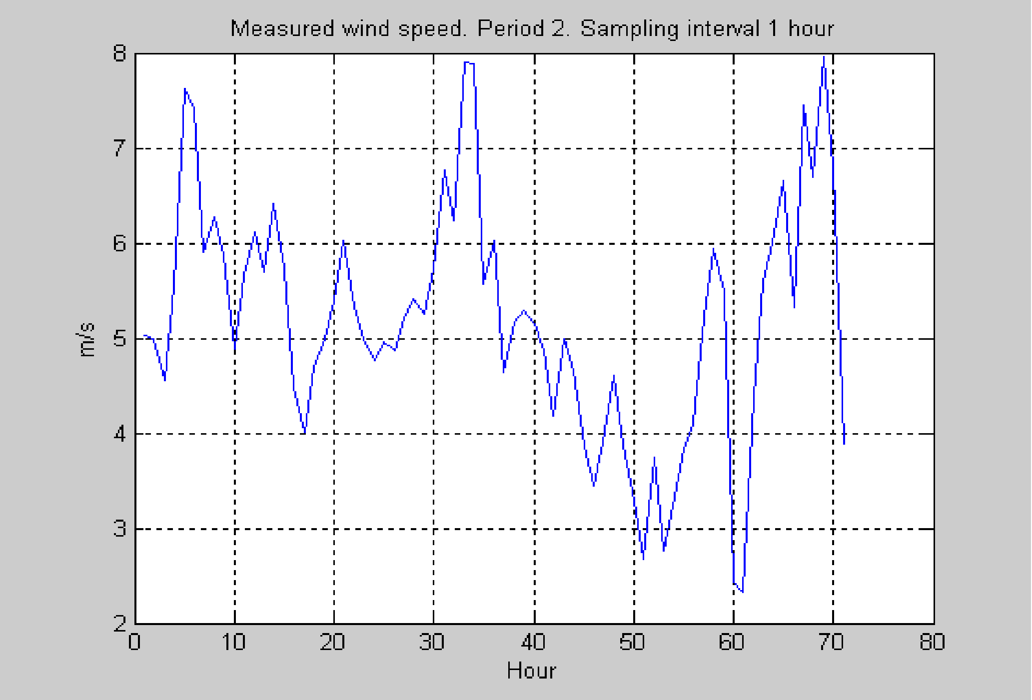

Figure 4 Measured wind speed. Period 2.
Mean value during a sampling period of 1 hour

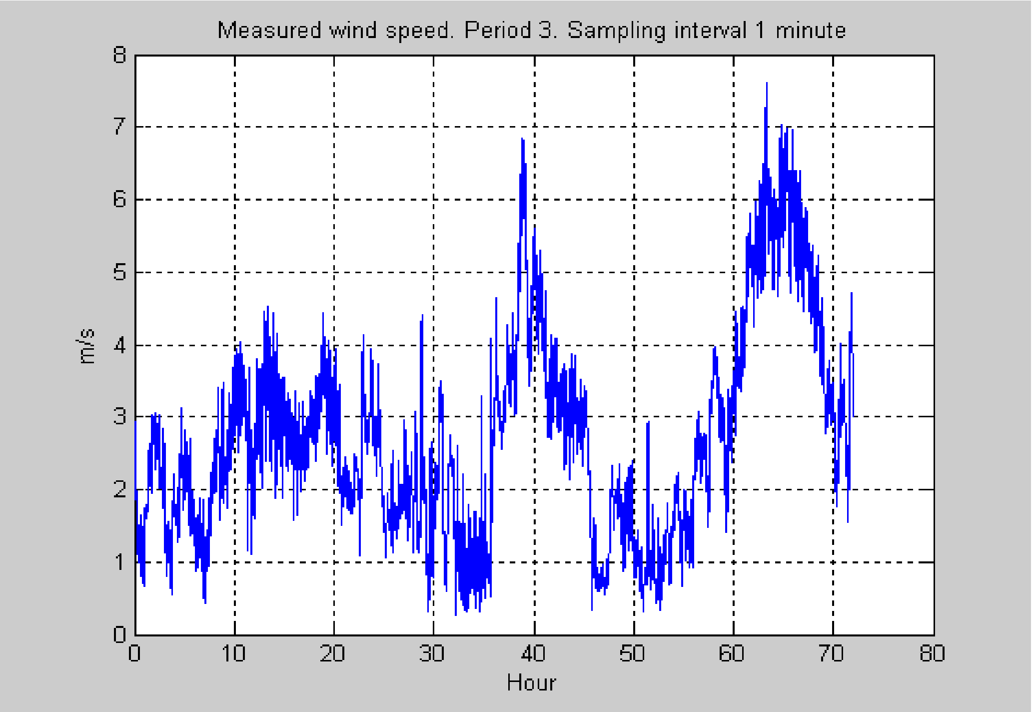

Figure 5 Measured wind speed. Period 3.
Mean value during a sampling period of 1 minute

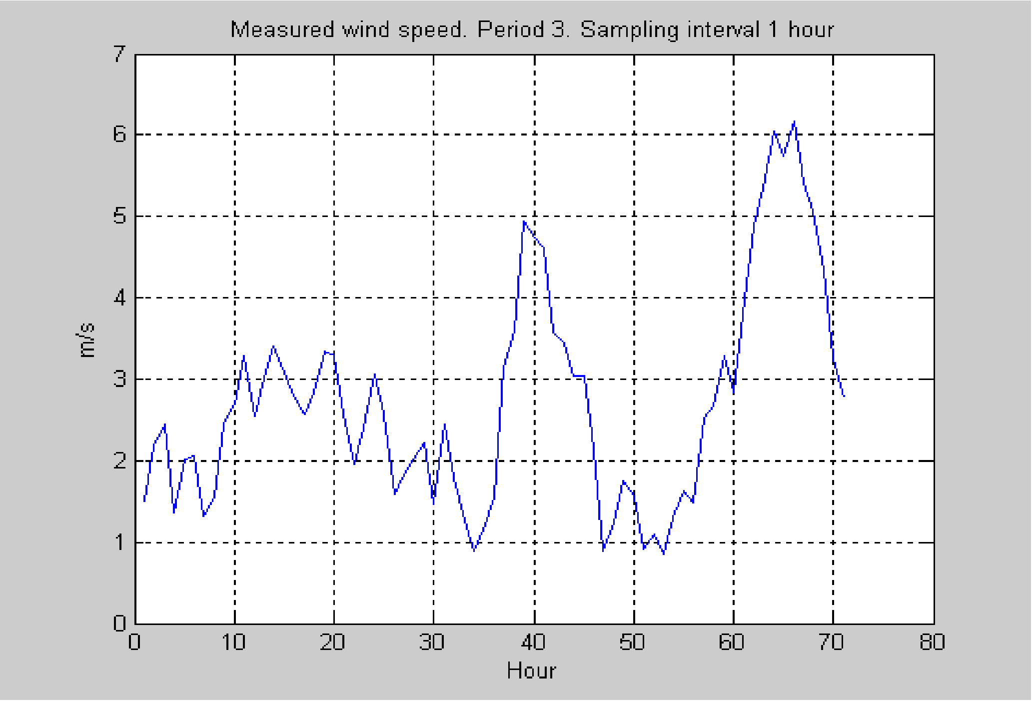

Figure 6 Measured wind speed. Period 3.
Mean value during a sampling period of 1 hour

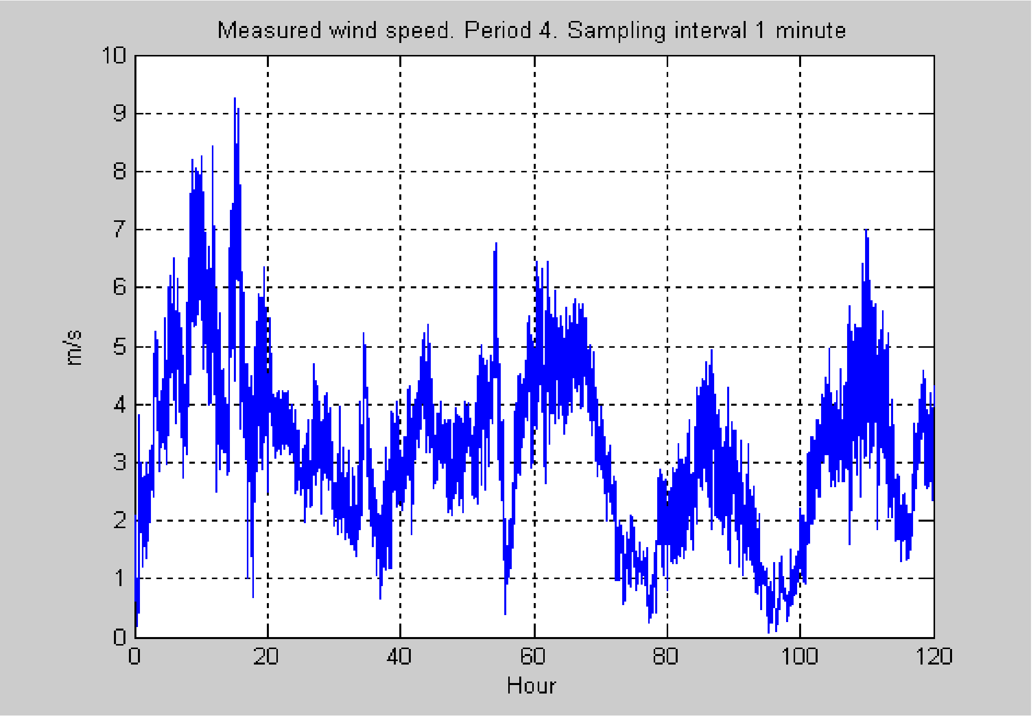

Figure 7 Measured wind speed. Period 4.
Mean value during a sampling period of 1 minute

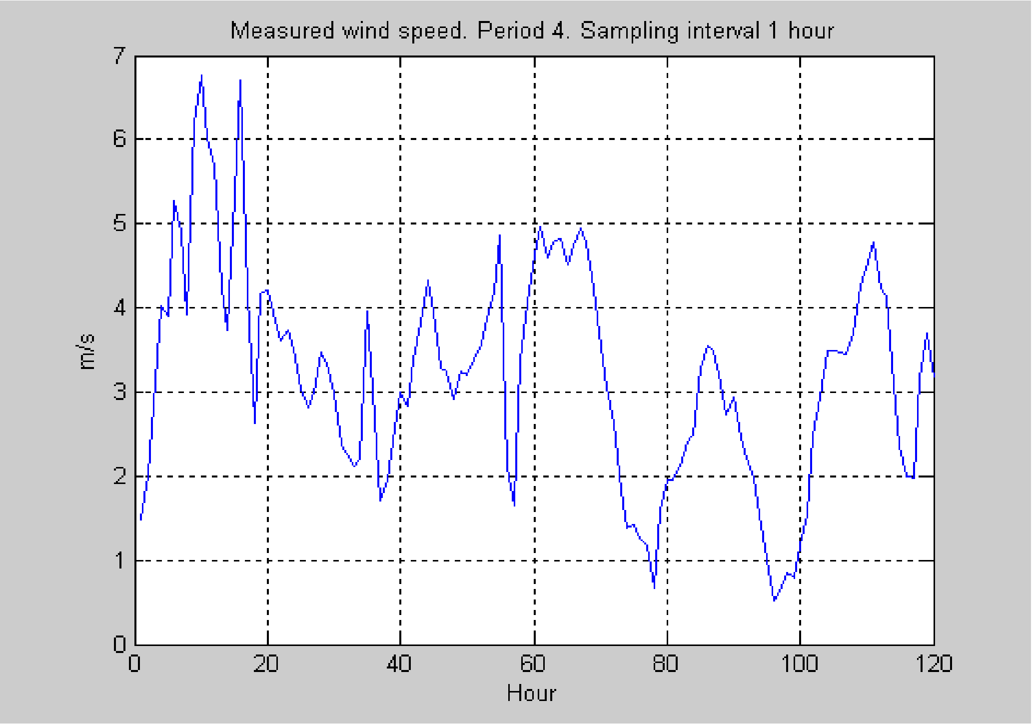

Figure 8 Measured wind speed. Period 4.
Mean value during a sampling period of 1 hour

3 EVALUATION OF MEASUREMENTS

3.1 Common

The evaluation is focused on parameters to be used in a stochastic model named ”Wind_make”. This model is described in point 3.2 and in reference [1] .

3.2 Wind_make

Wind_make is a program function (subroutine) with the purpose to generate stochastic wind speed data. The resulted data values are collected in a vector.

The wind speed values, in the following named v_wind, are generated as results of 1) weather variations and 2) turbulences. The total v_wind = Level_W + Level_T, where Lewel_W is a result of the weather situation and Level_T is a result of turbulence. Level_W is also named “the low frequency component” and Level_T “the high frequency component”. See Figure 9.

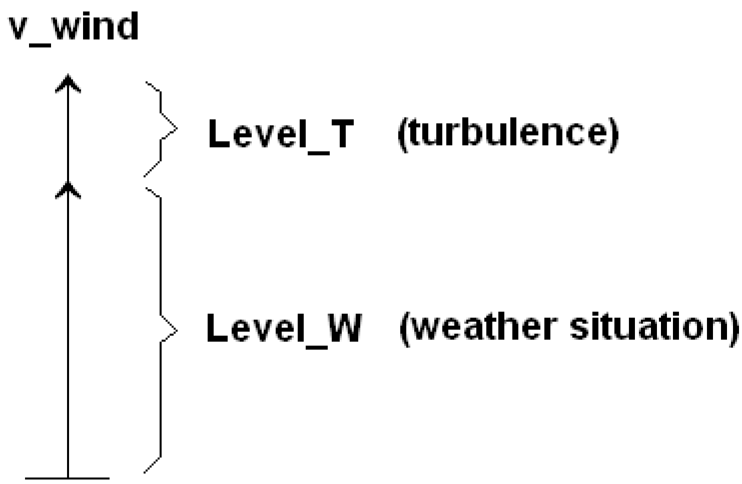

Figure 9 The wind speed is built up by two components, Level_W and Level_T

Wind_make is used as a module in a total simulation program. A simulation sequence consists of an optional number of simulation steps (Sim_step_total). Each simulation sequence is, in respect of the routine Wind_make, divided into a number of W-cycles, where each cycle is characterized of a “specific” weather situation. See Figure 10.

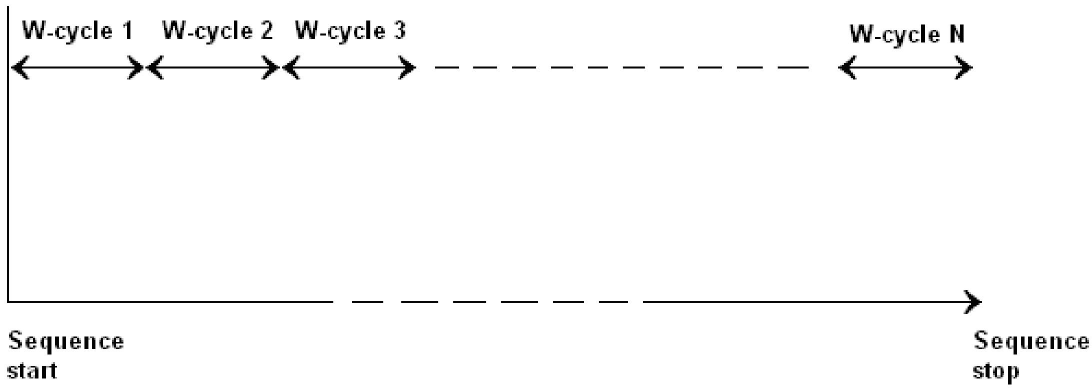

Figure 10 A total simulation sequence consists of a number (N) of W-cycles each of them representing a specific weather situation

The W-cycle contributes with a dominating “base” component to the wind speed. This base component, named Level_W, is stochasticly generated by a “Weibull distribution” according to:

Equation 1:

$$Level\_W = W(A, C)$$

Where W is a Weibull process and A respectively C are the “Weibull parameters”.

The Weibull distribution has the density function according to

Equation 2:

$$W(A,C) = \frac{C}{A}\left(\frac{S}{A}\right)^{C-1} e^{-\left(\frac{S}{A}\right)^{C}}$$

Where:

S: Level_W

A,C: Weibull parameters

The probability that “Level_W” not exceeds “S” follows by Equation 3.

Equation 3:

$$P(Level\_W \leq S) \quad = \quad \int_0^S W(A,C)dS \quad =$$

$$= \quad \int_0^S \frac{C}{A}\left(\frac{S}{A}\right)^{C-1} e^{-\left(\frac{S}{A}\right)^{C}} dS \quad = \quad 1 \quad - \quad e^{-\left(\frac{S}{A}\right)^{C}}$$

A new generation is performed for every W-cycle.

There is a “soft linear” transition from one W-cycle to another. That means that the new valuel of Level_W is gradually and linearly assigned over the total W-cycle time in question. Figure 11 illustrates how the “low frequency component is gradually and linearly shifted during the time interval corresponding to the W-cycle in question.

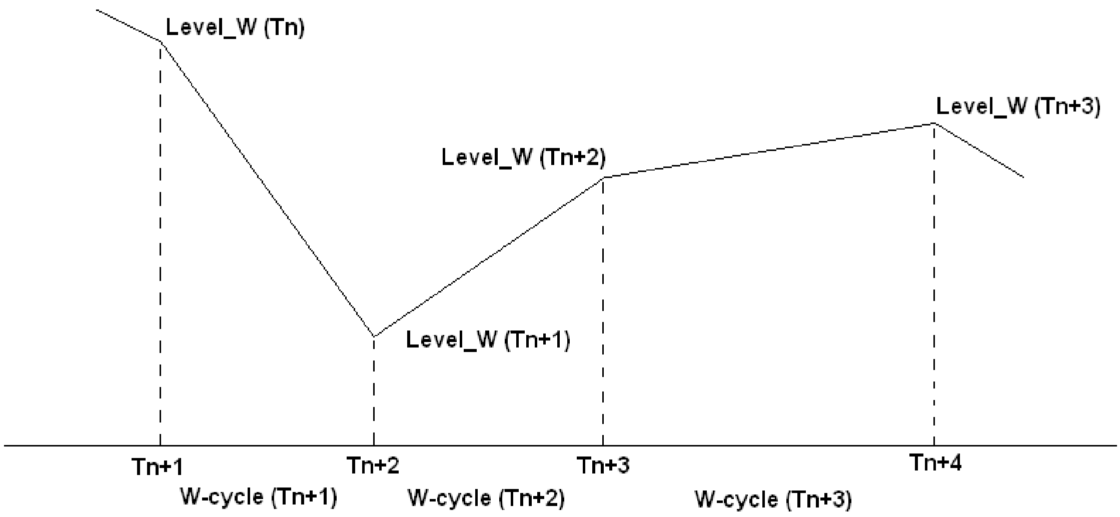

Figure 11 Lewel_W is linearly assigned during the different W-cycle times

Level_W(Tn): Level_W stochastically generated at time point Tn
W-cycle(Tn): W-cycle between time points Tn and Tn_{+1}

As may be seen in Figure 11 the different levels are delayed and get their final values at the end of respective W-cycle. For example: Level_W (Tn+1) is stochasticly generated at time point Tn+1 and is then linearly distributed during the total W-cycle (Tn+1), Level_W (Tn+2) is stochasticly generated at time point Tn+2 and is then linearly distributed during the total W-cycle (Tn+2), and so on.

The number of simulation steps in a W-cycle, *Sim_step_W_total*, is stochasticly generated according to Equation 4.

Equation 4:

Sim_step_W_total = $N(\mu, \sigma)$

Where:

N: a normal process
μ: an assigned mean value of simulation steps per W-cycle (*Sim_step_W_M*y)
σ: an assigned standard deviation of simulation steps per W-cycle (*Sim_step_W_Sigma*)

The Normal distribution follows according to Equation 5.

Equation 5:

$$N(\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Each W-cycle consists of a number of T-cycles. See Figure 12.

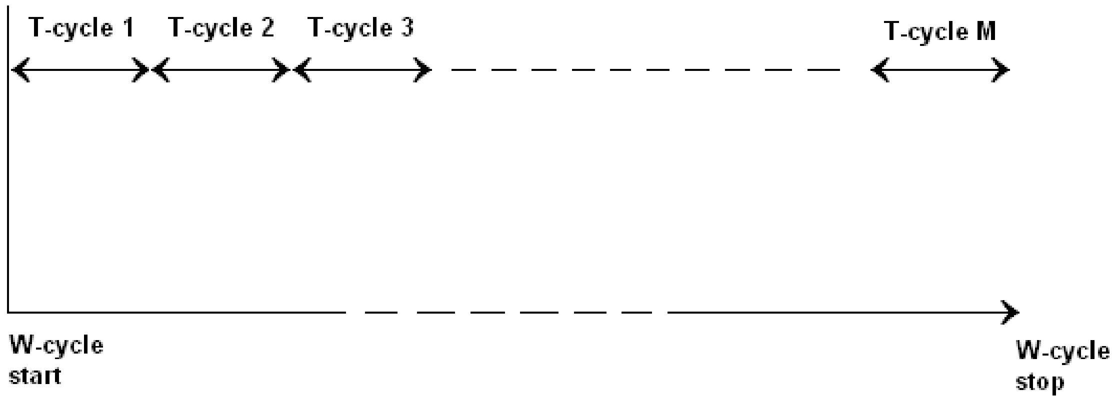

Figure 12 Every W-cycle is divided into a number (M) of T-cycles each of them representing a certain turbulence situation

Each T-cycle depends on an individual turbulence situation, that is varied from T-cycle to T-cycle. The contribution, Level_T , to the total wind speed, v_wind (see above), is generated by a "Normal distribution" according to:

Equation 6:

$Level\_T = N(\mu,\sigma)$

Where:

N: a normal process

μ: an assigned mean value of turbulence contribution per W-cycle (*Level_T_My*). *Level_T_My* is normaly assigned to zero, as the turbulence is proposed to fluctuate around the zero level.

σ: an assigned standard deviation of turbulence contribution per W-cycle (*Level_T_Sigma*)

The Normal distribution follows according to Equation 5.

The generated value of Level_T, is linearly distributed during the first half of the T-cycle. During the second half of the T-cycle the level returns to zero. See Figure 13.

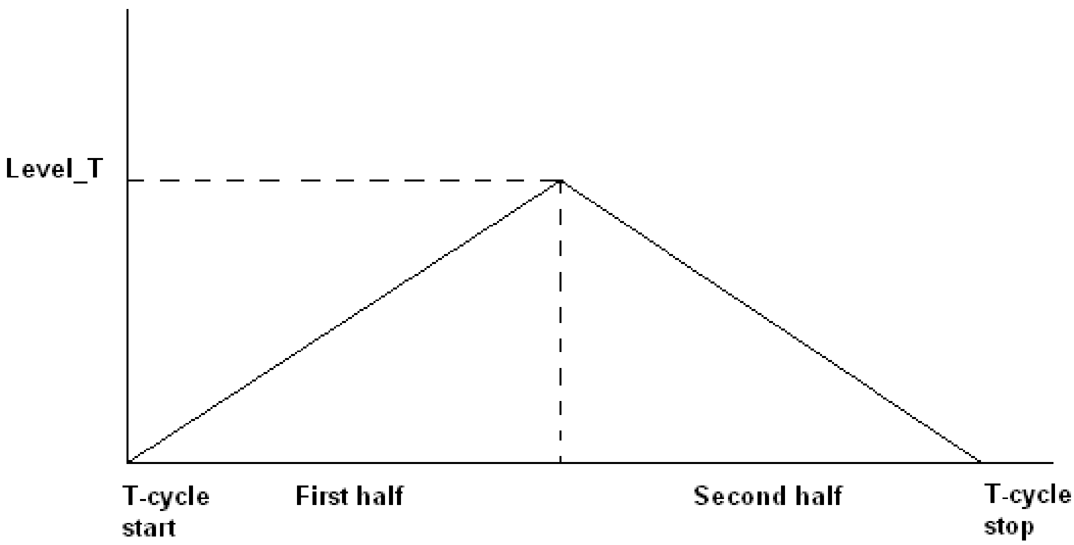

Figure 13 Distribution of Level_T during the T-cycle

The number of simulation steps for a single T-cycle, *Sim_step_T_total*, is stochasticly generated by a "Normal distribution" according to:

Equation 7:

$$Sim\_step\_T\_total = N(\mu,\sigma)$$

Where:

N: a normal process

μ: an assigned mean value of number of simulation steps per T-cycle (*Sim_step_T_My*)

σ: an assigned standard deviation of number of simulation steps per T-cycle (*Sim_step_T_Sigma*)

The Normal distribution follows according to Equation 5.

The input parameters to the routine follow in Table 1.

Parameter name	**Purpose**
Sim_step_sec Input via function argument from Main Program	Time interval in seconds per simulation step (60 is a standard value)
Sim_step_total Input via function argument from Main Program	The total number of simulation steps per sequence (Sim_step_total = 43200 corresponds to a simulation sequence over a time of 30 days if Sim_step_sec = 60)
Sim_step_W_My	Mean value of the number of simulation steps per W-cycle (Sim_step_W_My = 4320 corresponds to a mean value of 3 days (3 times 24 hours) if Sim_step_sec = 60)
Sim_step_W_Sigma	Standard deviation of the number of simulation steps per W-cycle
Sim_step_T_My	Mean value of the number of simulation steps per T-cycle (Sim_step_T_My = 10 corresponds to a mean value of 10 minutes if Sim_step_sec = 60)
Sim_step_T_Sigma	Standard deviation of the number of simulation steps per T-cycle
A	Weibull parameter (scale parameter)
C	Weibull parameter (shape parameter)
Level_T_Sigma_proc	Standard deviation of Level _T in percent of Level_W
v_wind_H	Upper limit of the wind speed
v_wind_L	Lower limit of the wind speed
Wind_speed_file	The name of a *Wind speed file* (string) to store the wind speed vector and the above parameters in this table

Table 1 Input parameters for routine “Wind_make”

The parameters according to Table 2 will be avaluated based on the measurements presented in chapter 1 and chapter 2.

Parameter name	Purpose
Sim_step_W_My	Mean value of the number of simulation steps per W-cycle (Sim_step_W_My = 4320 corresponds to a mean value of 3 days (3 times 24 hours) if Sim_step_sec = 60)
Sim_step_W_Sigma	Standard deviation of the number of simulation steps per W-cycle
Sim_step_T_My	Mean value of the number of simulation steps per T-cycle (Sim_step_T_My = 10 corresponds to a mean value of 10 minutes if Sim_step_sec = 60)
Sim_step_T_Sigma	Standard deviation of the number of simulation steps per T-cycle
A	Weibull parameter (scale parameter)
C	Weibull parameter (shape parameter)
Level_T_Sigma_proc	Standard deviation of Level _T in percent of Level_W

Table 2 Parameters that are evaluated based on the measurements in question

3.3 Methods for evaluation

There are some important criterions that are to be fulfilled when the parameters in Table 2 are adapted to the measurements in question. The adaption is in principle performed by model simulations and varying some model parameters in order to get a good similarity between measurements and simulated results. There are some characteristics that will be used in the evaluation process. These characteristic parameters are:

- Energy band
- Discrete Frequency Function
- Mean value of the kinetic wind energy
- Mean value and Standard deviation of the wind rate
- Maximum and Minimum value of the wind rate

3.3.1 Energy Band

The kinetic wind energy spectrum is divided into a number of discrete energy bands. These bands are defined according to Equation 8 to Equation 10. See also paragraph 3.3.2.

Equation 8:

$$Band(1) = \sum_n Wn(V)$$

Where:

Band(1): integrated normalized energy in lowest band. The principle of normalized energy follows in paragraph 3.3.2.

$W_n(V)$: normalised kinetic wind energy as a function of vind rate V, time point n. $W_n(V$ is for *Band(1)* defined as $W_n < k_1 \cdot W_{mean,}$ $k_1 = k_{min}$

W_{mean}: normalised mean energy of the process

k_{min}: defined parameter. In this study $k_{min} = 0.2$

Equation 9:

$$Band(n) = \sum_n W_n(V), \qquad n = 2, 3, \ldots\ldots, N\text{-}1$$

Where:

Band(n): integrated normalized energy in band n.

$W_n(V)$: normalised kinetic wind energy as a function of vind rate V, time point n. $W_n(V)$ is for *Band(n)* defined as $k_{n-1} \cdot W_{mean} \le W_n(V) < k_n \cdot W_{mean}$, $k_n = k_{min} + (n-1) \cdot k_{band}$, $n = 2, 3, \ldots\ldots, N-1$

N: number of bands. In this study $N = 52$

k_{band}: defined parameter. In this study $k_{band} = 0.2$

Equation 10:

$$Band(N) \quad = \quad \sum_{n} W_n(V)$$

Where:

Band(N): integrated normalized energy in highest band

$W_n(V)$: normalised kinetic wind energy as a function of vind rate V, time point n. $W_n(V)$ is for *Band(N)* defined as $k_{N-1} \cdot W_{mean} \quad \leq \quad W_n(V)$,
$k_{N-1} = k_{\min} + (N-1) \cdot k_{band}$

3.3.2 Normalised Energy

A definition of what in this paper is named the *Normalised Energy* follows in Equation 11.

Equation 11:

$$W_{Normalised}(V) = \frac{W(V) \cdot \Delta V}{\int_{V\min}^{V\max} W(V)\, dV}$$

Where:

$W_{Normalised}(V)$:	normalized (kinetic) energy per m^2 (perpendicular to the wind direction) at the wind rate *V*
W(V):	measured or simulated kinetic wind energy per second and per m^2 (perpendicular to the wind direction) at the wind rate *V*
V:	a defined wind speed
ΔV:	a small wind rate region quite around *V*
Vmin:	minimum wind rate of the process
Vmax:	maximum wind rate of the process

If the function $W_N(V)$ is regarded in a specific wind rate region, for instance an energy band, it could be defined according to Equation 12:

Equation 12:

$$W_N(b) = \frac{\int_{V_{Band}(b)}^{V_{Band}(b)+d_{Band}(b)} W(V)\,dV}{\int_{V\min}^{V\max} W(V)\,dV}$$

Where:

$W_N(b)$:	normalized (kinetic) energy per m^2 (perpendicular to the wind direction) in the energy band *b*
$V_{Band}(b)$:	a function that gives the lower wind rate limit for energy band *b*

$d_{Band}(b)$: a function that gives the wind rate interval for energy band b

Equation 12 could be expressed according to Equation 13.

Equation 13:

$$W_N(b) = \frac{\int_{V_{Band}(b)}^{V_{Band}(b)+d_{Band}(b)} C \cdot V^3 \cdot f(V)\, dV}{\int_{V\min}^{V\max} C \cdot V^3 \cdot f(V)\, dV} = \frac{\int_{V_{Band}(b)}^{V_{Band}(b)+d_{Band}(b)} V^3 \cdot f(V)\, dV}{\int_{V\min}^{V\max} V^3 \cdot f(V)\, dV}$$

Where:

C: $\frac{1}{2}\rho$, where ρ is the air density (kg/m^3). If ρ could be assumed to be constant, then the parameter C is a constant

$f(V)$: a continous function that gives the relative frequency of the wind speed V

Equation 13 could be expressed in an **approximative and discretisied** form according to Equation 14.

Equation 14:

$$W_N(b) = \frac{\sum_{V(b)}^{V(b)+d(b)} V^3 \cdot g(V)}{\sum_{V_{\min}}^{V_{\max}} V^3 \cdot g(V)}$$

Where:

$W_N(b)$: normalized (kinetic) energy per m^2 (perpendicular to the wind direction) in the energy band *b*

g(V): a discrete frequency function that gives the frequency (number) of measured/calculated samples with different wind rates *V*. In this study these samples are counted over a time period of 72 hours respectively 120 hours, corresponding to the 4 periods according to chapter 1.

3.3.3 Mean value of the kinetic wind energy

The mean value of the kinetic wind energy from all energy bands results in a good measure regarding a specific wind situation. This parameter is compared in respect of simulated results and corresponding measure values.

3.3.4 Mean value and Standard deviation of the wind rate

The mean value and standarddeviation of the wind rate ($V\mu$ *and* $V\sigma$) is based on the total number of samples during the measuring/simulation interval (period). It is defined according to Equation 15 and Equation 16.

Equation 15:

$$V\mu = \frac{\sum_{k=1}^{N} M(k)}{N}$$

Where:

$V\mu$: mean value of wind rate during the period in question

M(k), N: measurement/simulation value regarding wind rate at time point *k*

N: number of time points

Equation 16:

$$V\sigma \quad = \quad \sqrt{\frac{\sum_{k=1}^{N}\left(M(k) - V\mu\right)^2}{N-1}}$$

Where:

Vσ: standarddeviation of the wind rate during the period in question

Vμ, M(k), N: see Equation 15

3.3.5 Maximum and Minimum value of the wind rate

The Maximum and Minimum value of the wind rate (*Vmax and Vmin*) is based on the total number of samples during the measuring/simulation interval (period). It is defined according to Equation 17 and Equation 18.

Equation 17:

$$V\max \quad = \quad \max imum\{M(k)\},\ k = 1 \rightarrow N$$

Where:

M(k), N: see Equation 15

Equation 18:

$$V\max \quad = \quad \min imum\{M(k)\},\ k = 1 \rightarrow N$$

Where:

M(k), N: see Equation 15

4 SIMULATIONS

As is mentioned in 3.3 the parameters in Table 2 are adapted to the measurements by model simulations and varying some model parameters in order to get a good similarity between measurements and simulated results. In Table 3 and Table 4 the adapted results from simulations are collected for the 4 measuring periods in question. The tables give recommended (nominal) values for the model parameters.

Measuring period (see chapter 1)	Weather variation		Turbulence variation		Turbulence level
	Sim_step _W_My	Sim_step _W_Sigma	Sim_step _T_My	Sim_step _T_Sigma	Level_T _Sigma_proc
1	300	100	3	1	35
2	300	100	3	1	15
3	300	100	3	1	20
4	300	100	3	1	30

Table 3 Resulting nominal model parameters after comparering measuring results with simulation results

Measuring period (see chapter 1)	Weibull parameters	
	A	C
1	4.80	3.12
2	5.80	3.60
3	3.30	2.40
4	3.80	2.50

Table 4 Resulting nominal model parameters after comparering measuring results with simulation results

4.1 Measuring period 1

Date: 27 – 29 May 2007 (72 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 15 - Figure 21 and in Table 5 and Table 6 the comparisons are presented.

Comments regarding figures and tables

Figure 15 - Figure 18 The graphs give the correlation between the *Energy Bands* and corresponding wind rates. The following model parameters have been altered:

- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 4.8 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 3.12 gives the best adaption to the measurement result
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 35 % gives the best adaption to the measurement result
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3,1)[*)] gives the best adaption to the measurement result.

Figure 19 The graphs give the correlation between the *Energy Bands* and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). Simulation with nominal parameters is compared with measurement result.

Figure 20 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific *Wind rate Bands* (defined by wind rates) and the *Wind rate Bands* in question. (Frequency function vs wind rate band).
See Figure 14 and Equation 19. The figure illustrates 52 *Wind rate Bands*, separated with 0.2 m/s. The equation defines the correlation between *Wind rate Bands* and *Wind rates*. Simulation with nominal parameters is compared with measurement result.

Figure 21 and Figure 22 The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 1

Table 5 lists the resulting *Quotient of Relative Mean Energy* between simulation and measurement during period 1. As can bee noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 6 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement results.

*) mean value: 3, standarddeviation: 1

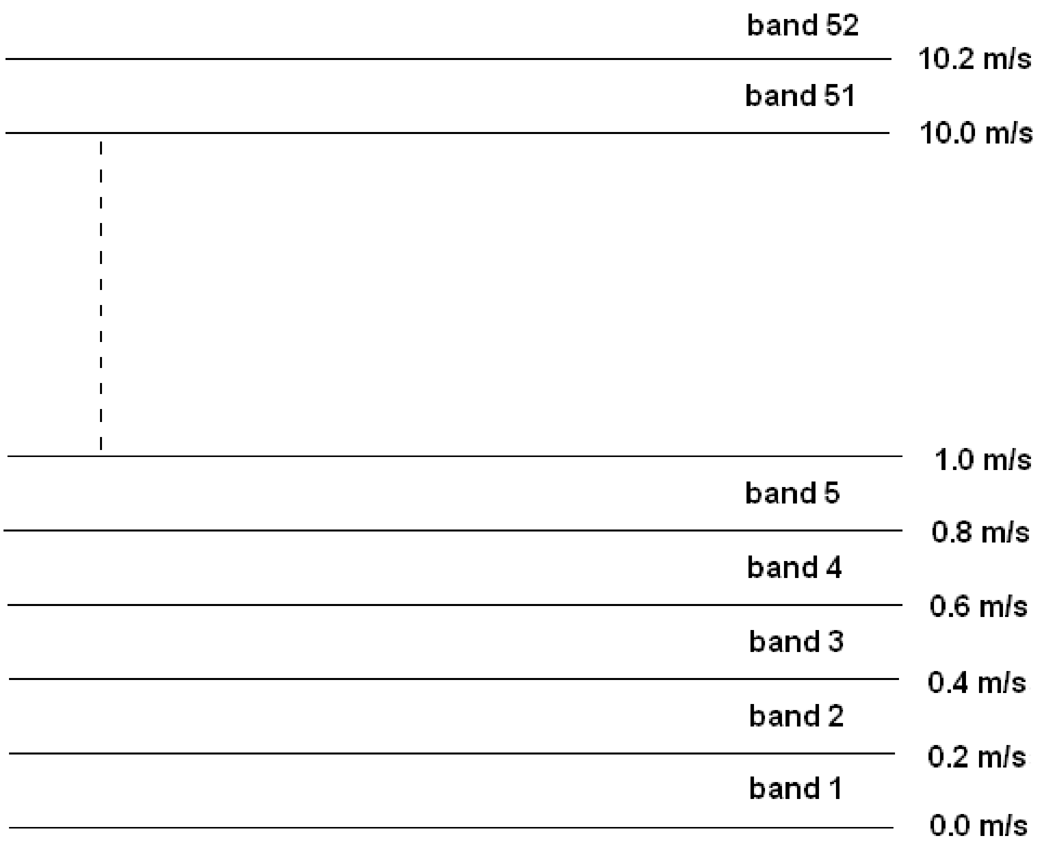

Figure 14 *"Wind rate Bands"* 1 to 52. The *Wind rate Bands* are defined according to Equation 19.

Equation 19:

$$Wind\ rate\ Band\ N, \quad N = 1 \rightarrow 51: \qquad (N-1)\cdot 0.2\ m/s \ \leq \ wind\ rate \ < \ N\cdot 0.2\ m/s$$

$$Wind\ rate\ Band\ 52: \qquad wind\ rate \ \geq \ 10.2\ m/s$$

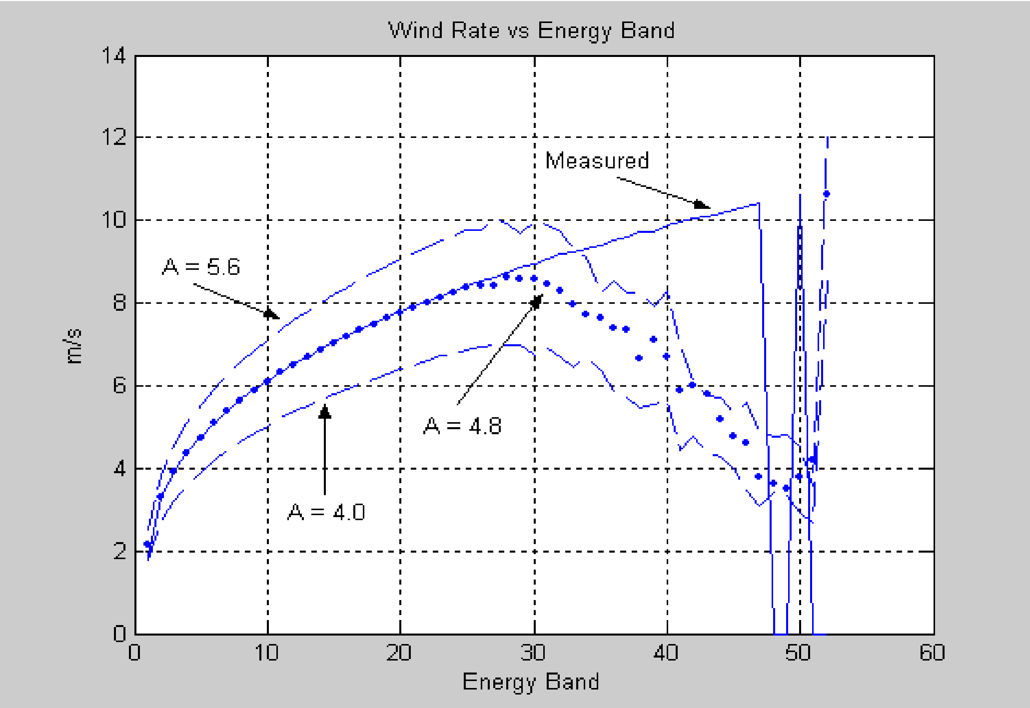

Figure 15 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

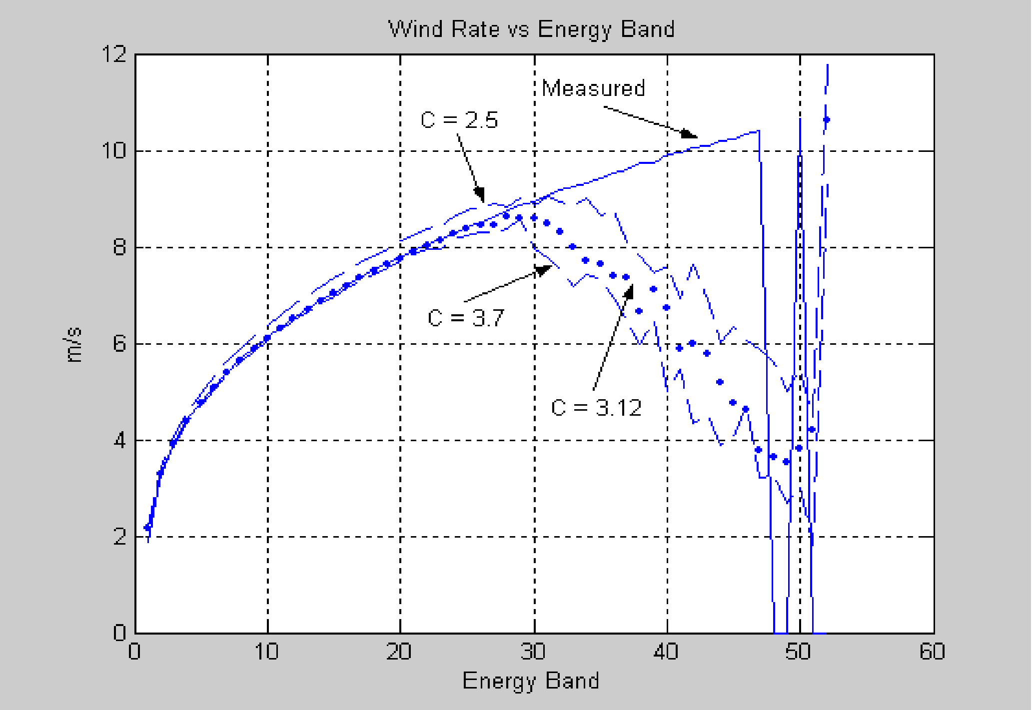

Figure 16 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

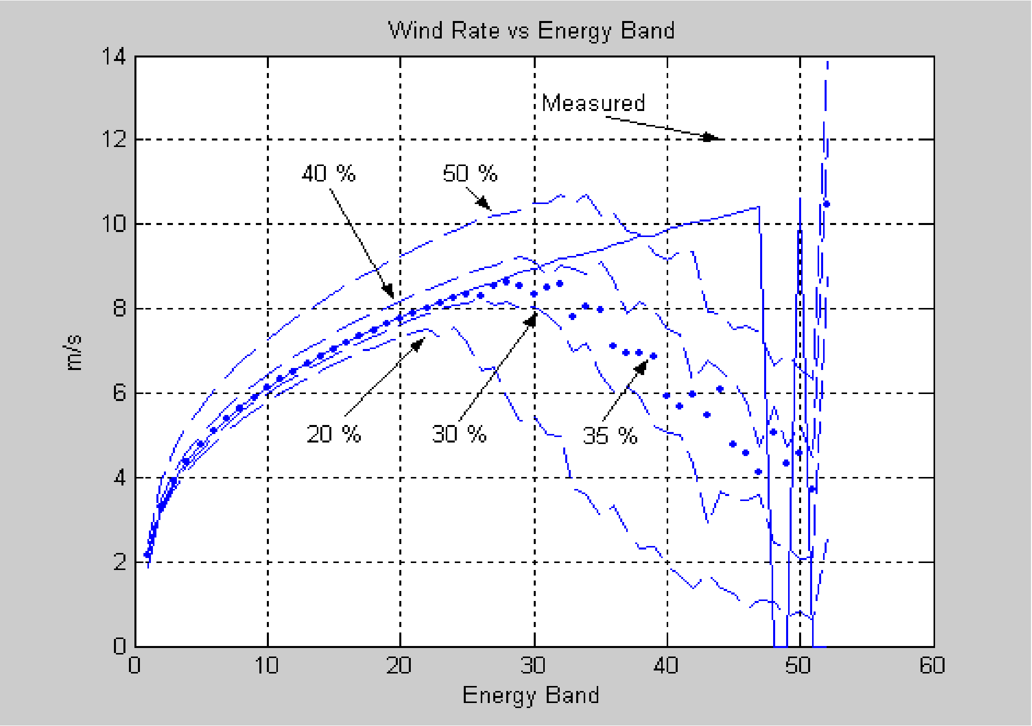

Figure 17 Wind rate vs Energy Band with altering Turbulence level. (C, A and Turbulence variation are fixed nominal)

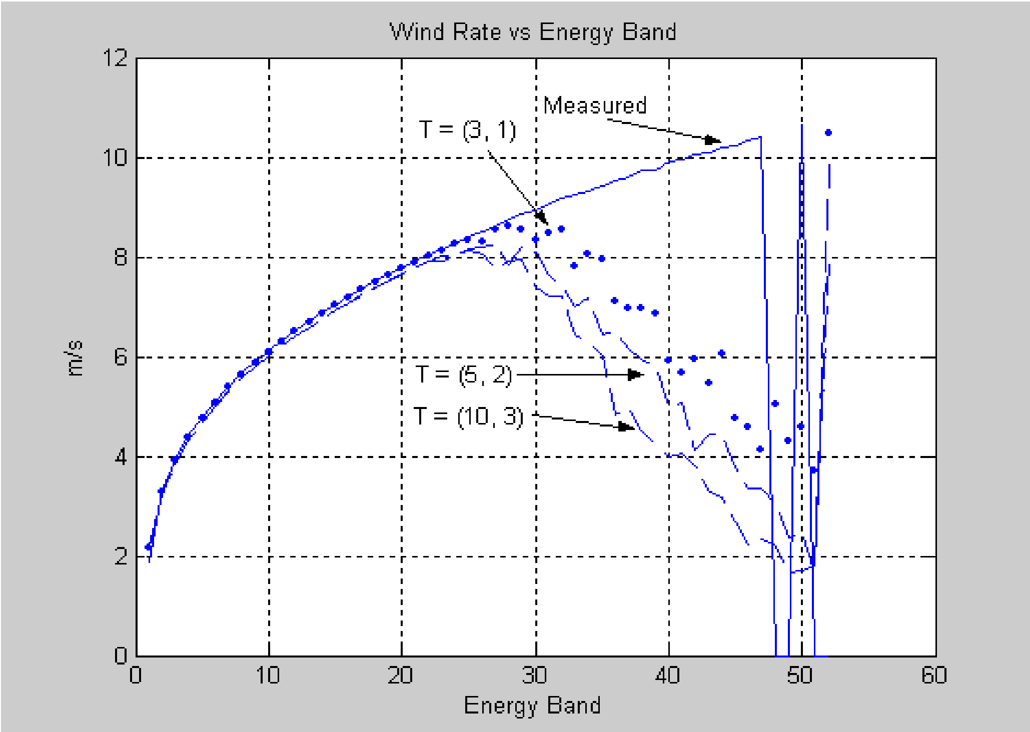

Figure 18 Wind rate vs Energy Band with altering Turbulence variation. (C, A and Turbulence are fixed nominal)

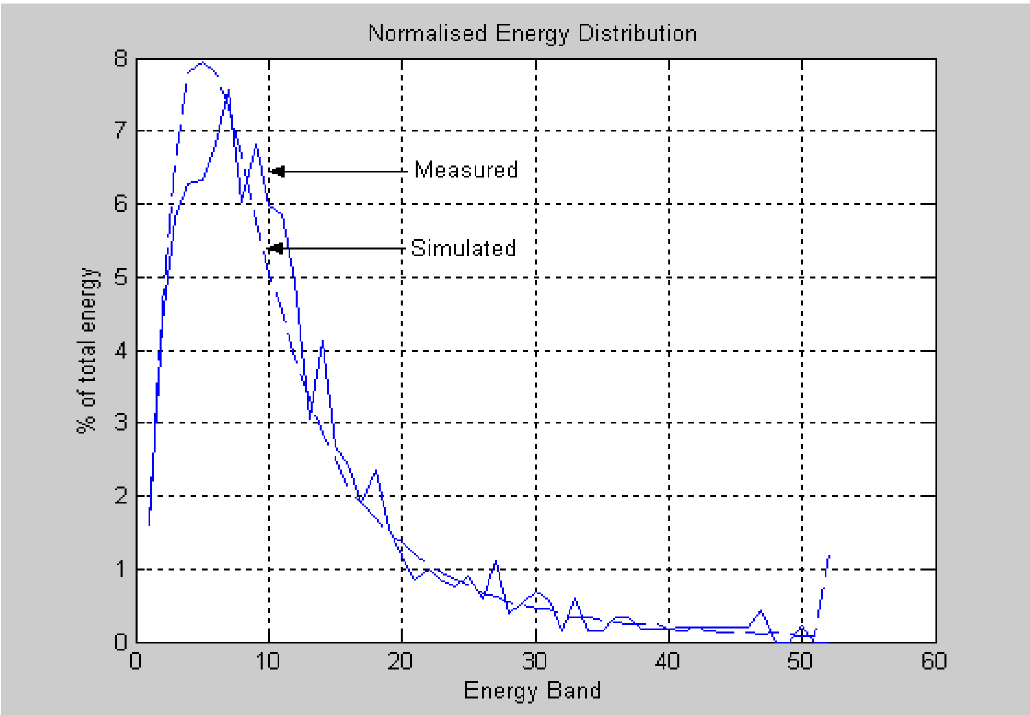

Figure 19 Normalised energy distribution vs energy band

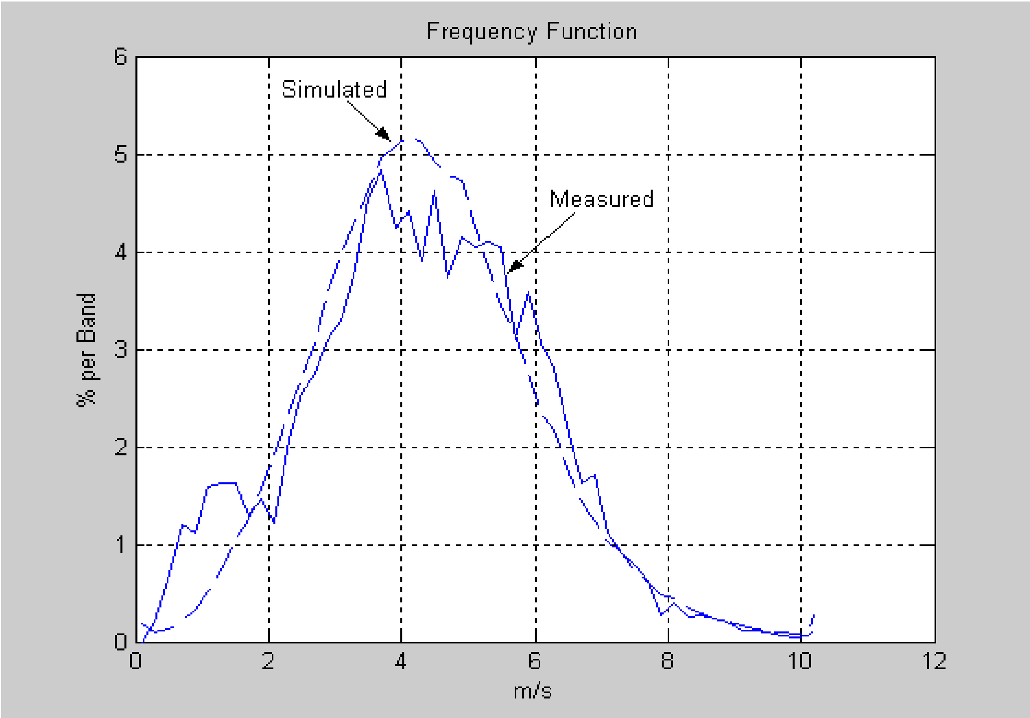

Figure 20 Frequency function vs wind rate band

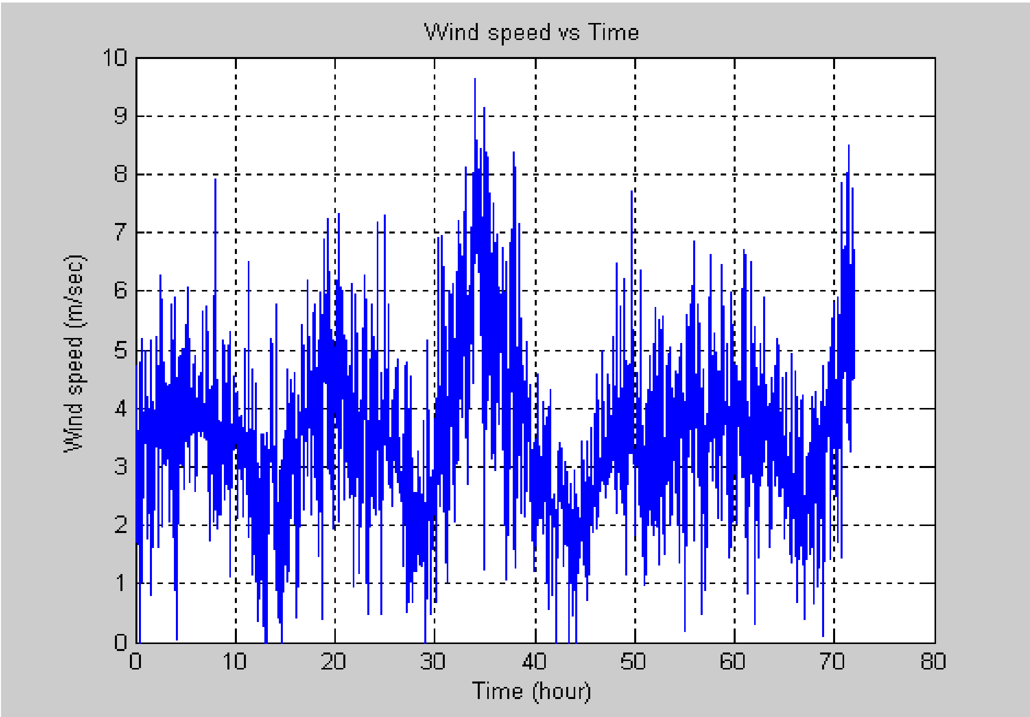

Figure 21 Simulated wind speed with nominal model parameters according to Table 3 and Table 4. Period 1

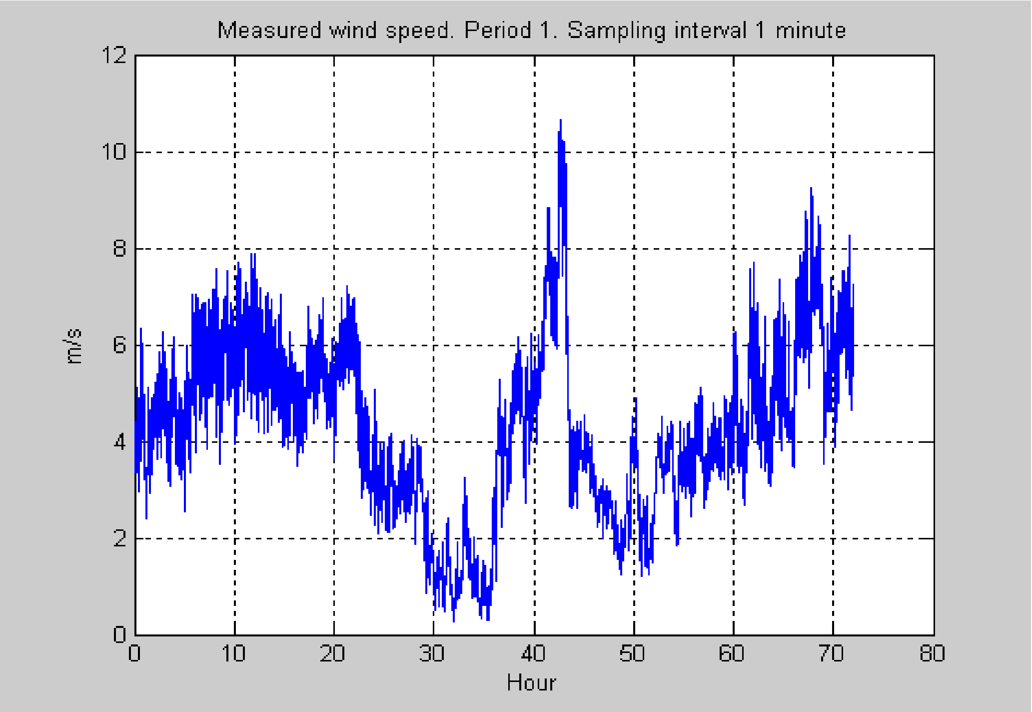

Figure 22 Measured wind speed. Period 1

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ Result}{Measurement\ Result}$
A (C, Turbulence and Turbulence variation nominal)	4.0	0.5785
	4.8 (nominal)	**1.0029**
	5.6	1.6157
C (A, Turbulence and Turbulence variation nominal)	2.5	1.0934
	3.12 (nominal)	**1.0029**
	3.7	0.9854
Turbulence (C, A and Turbulence variation nominal)	20 %	0.8523
	30 %	0.9254
	35 % (nominal)	**1.0029**
	40 %	1.1278
	50 %	1.7211
Turbulence variation (C, A and Turbulence nominal)	**(3,1)** (nominal)	**1.0029**
	(5,2)	0.9432
	(10,3)	0.9707

Table 5 Relative Mean Energy vs variation of some parameters

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
4.3	4.4	1.8	1.6	10.6	12.0	0.3	0.0

Table 6 Statistical parameters regarding wind rate. Measurements vs simulations

4.2 Measuring period 2

Date: 2 – 4 June 2007 (72 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 23 - Figure 33 and in Table 7 and Table 8 the comparisons are presented.

Comments regarding figures and tables:

Figure 23 -Figure 26 The graphs give the correlation between the *Energy Bands* and corresponding wind rates. The following model parameters have been altered:

- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 5.8 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 3.6 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 15 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)$^{*)}$ gives the best adaption to the measurement result.

Figure 27 - Figure 30 The graphs give the correlation between the *Energy Bands* and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). The following model parameters have been altered:

- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 3.6 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 15 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)$^{*)}$ gives the best adaption to the measurement result.

Figure 31 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific *Wind rate Bands* (defined by wind rates) and the *Wind rate Bands* in question. (Frequency function vs wind rate band).
See Figure 14 and Equation 19. The figure illustrates 52 *Wind rate Bands*, separated with 0.2 m/s. The equation defines the correlation between *Wind rate Bands* and *Wind rates*. Simulation with nominal parameters is compared with measurement result.

<u>*Figure 32 and Figure 33*</u> The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 2.

Table 7 lists the resulting *Quotient of Relative Mean Energy* between simulation and measurement during period 2. As can bee noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 8 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement result.

*) mean value: 3, standarddeviation: 1

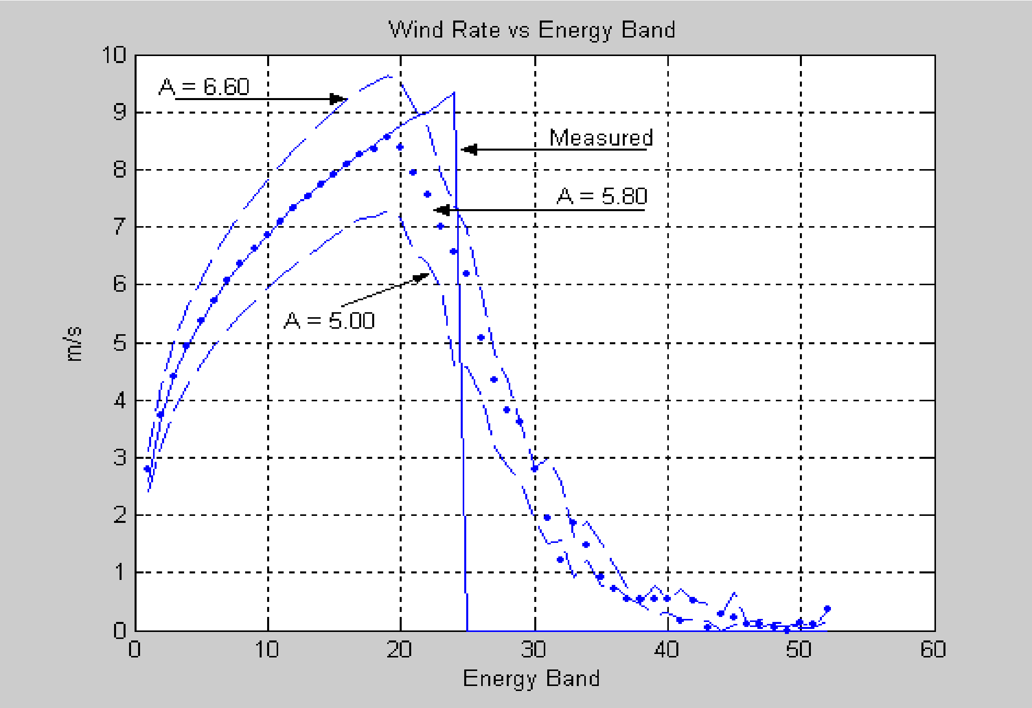

Figure 23 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

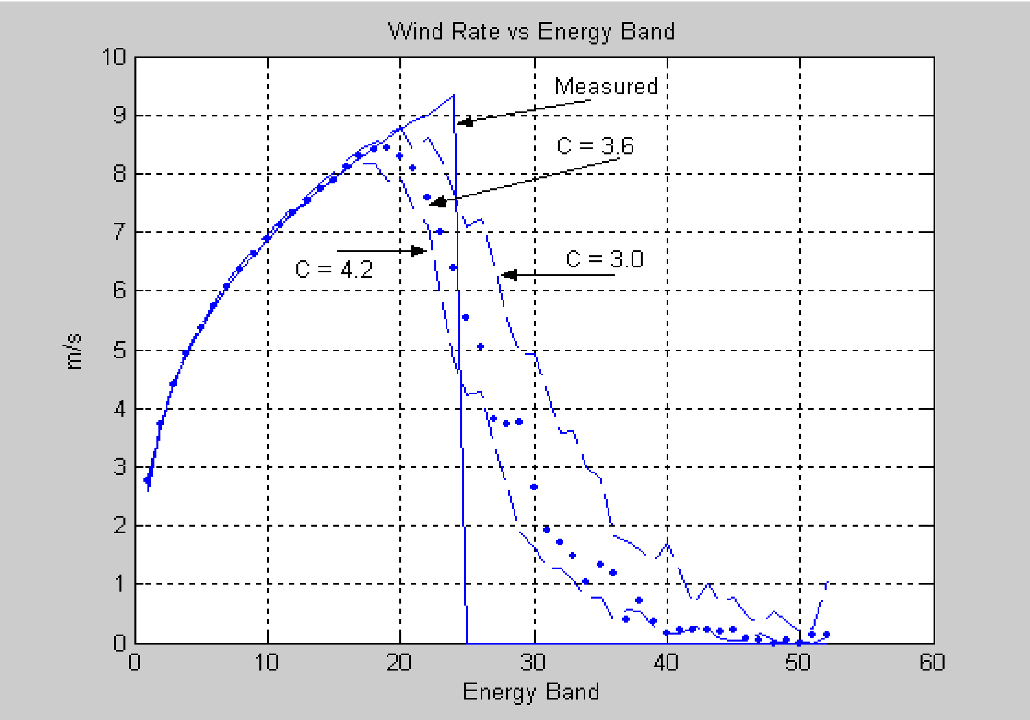

Figure 24 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

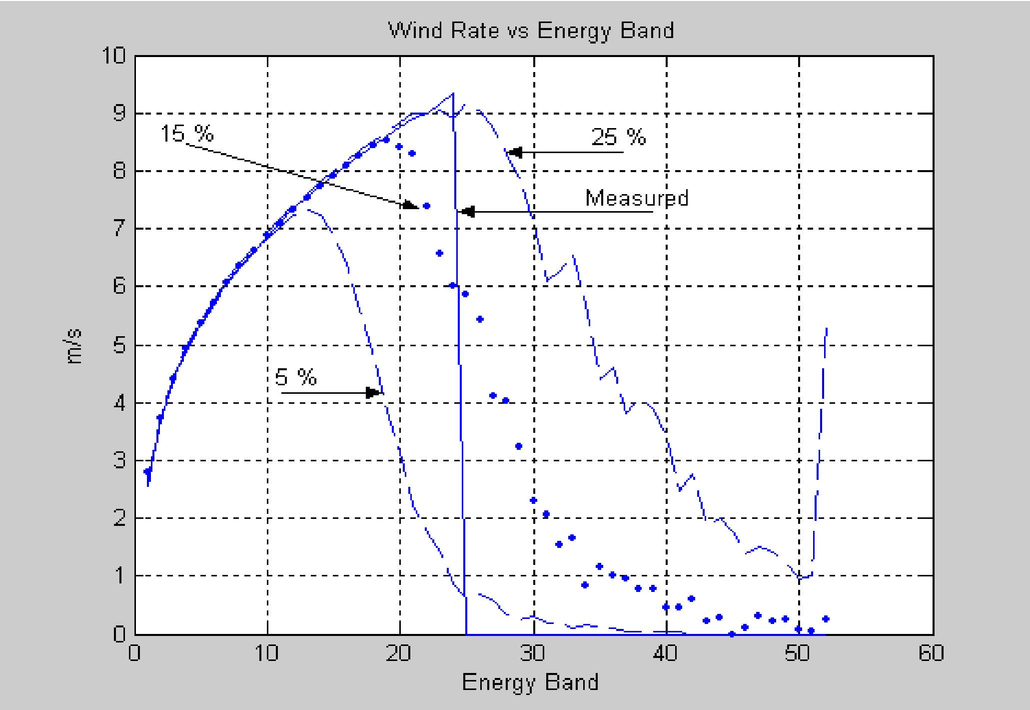

Figure 25 Wind rate vs Energy Band with altering Turbulence level. (A, C and Turbulence variation are fixed nominal)

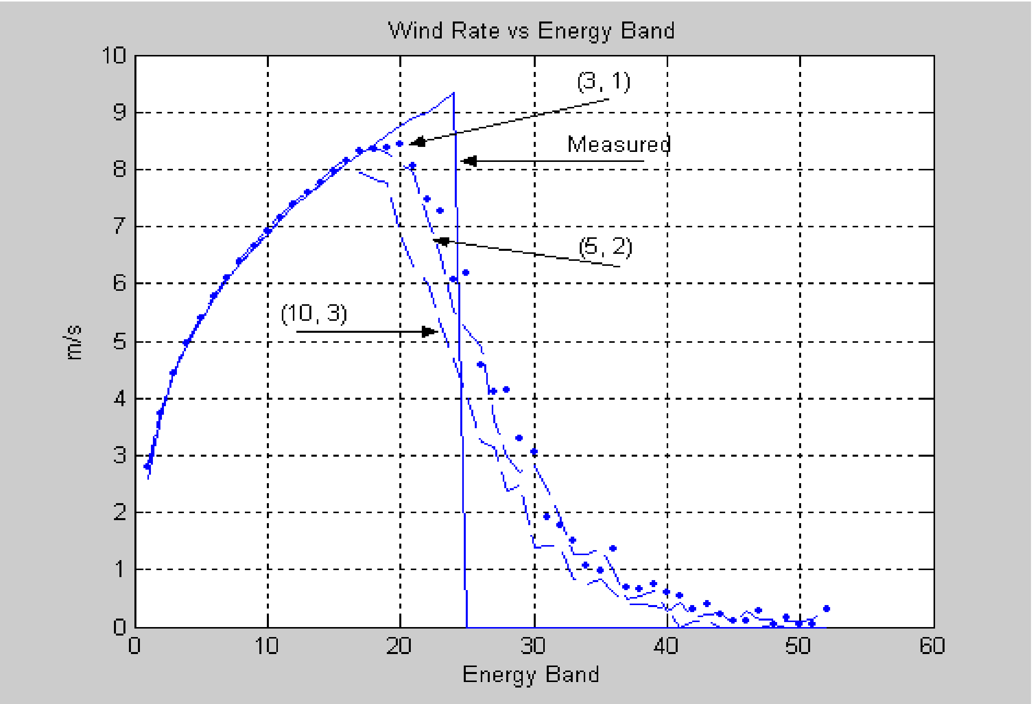

Figure 26 Wind rate vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

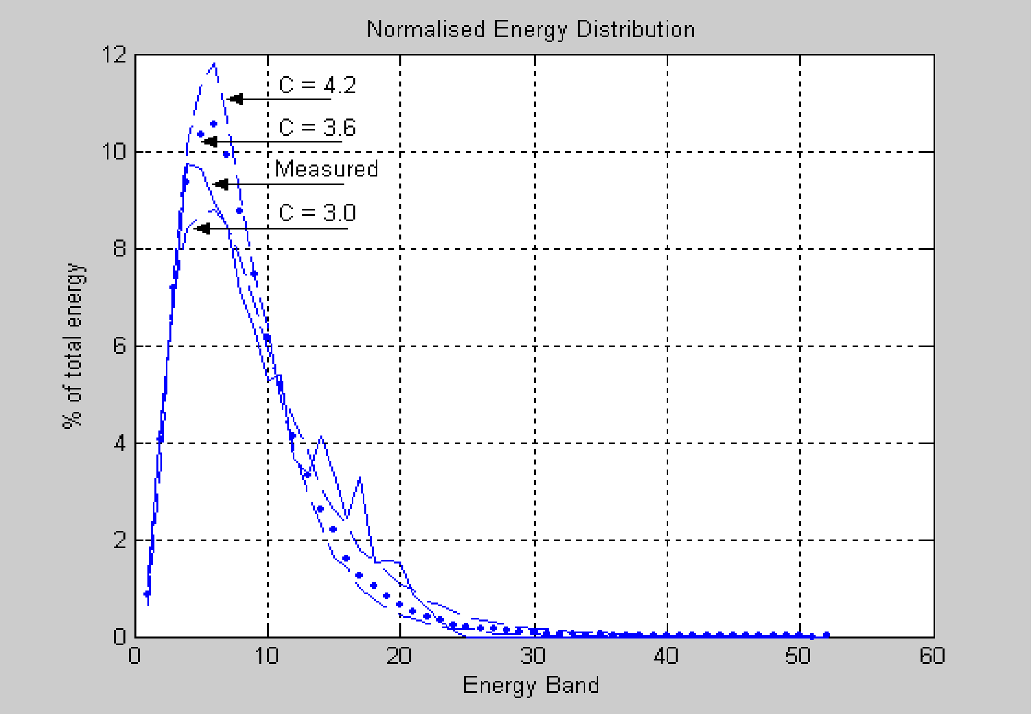

Figure 27 Normalised Energy Distribution vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

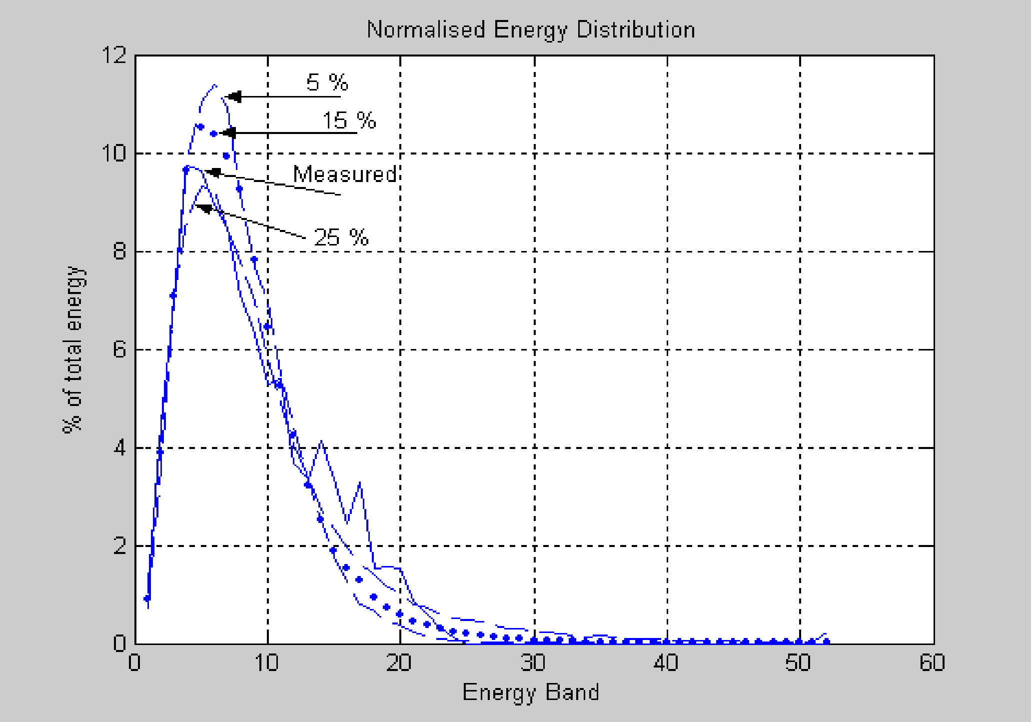

Figure 28 Normalised Energy Distribution vs Energy Band with altering Turbulence. (A, C and Turbulence variation are fixed nominal)

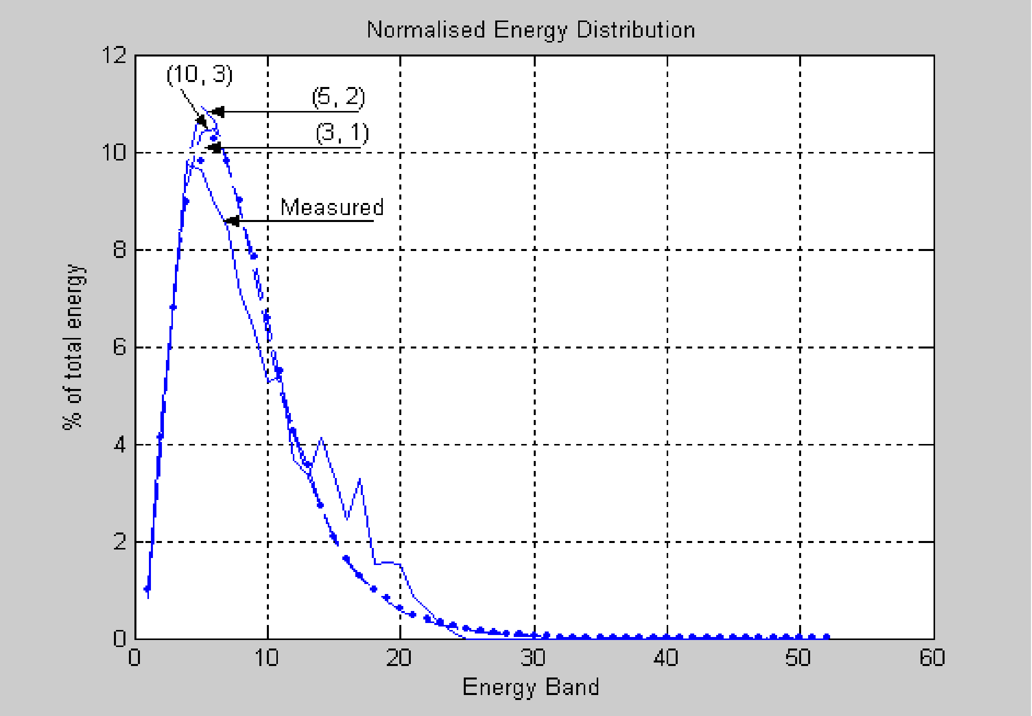

Figure 29 Normalised Energy Distribution vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

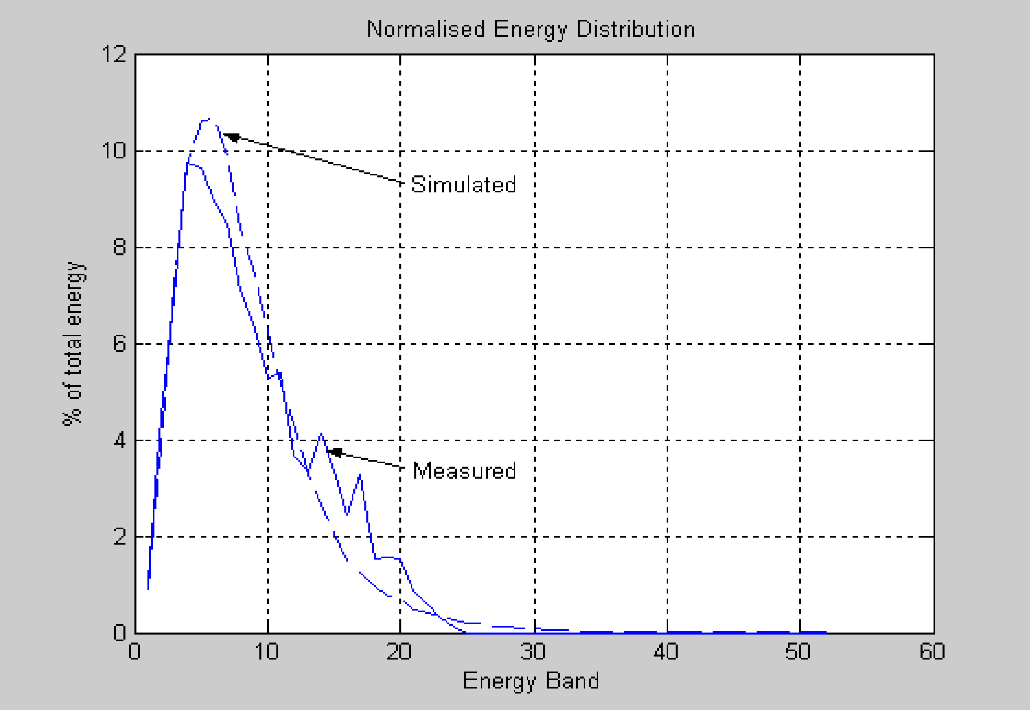

Figure 30 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

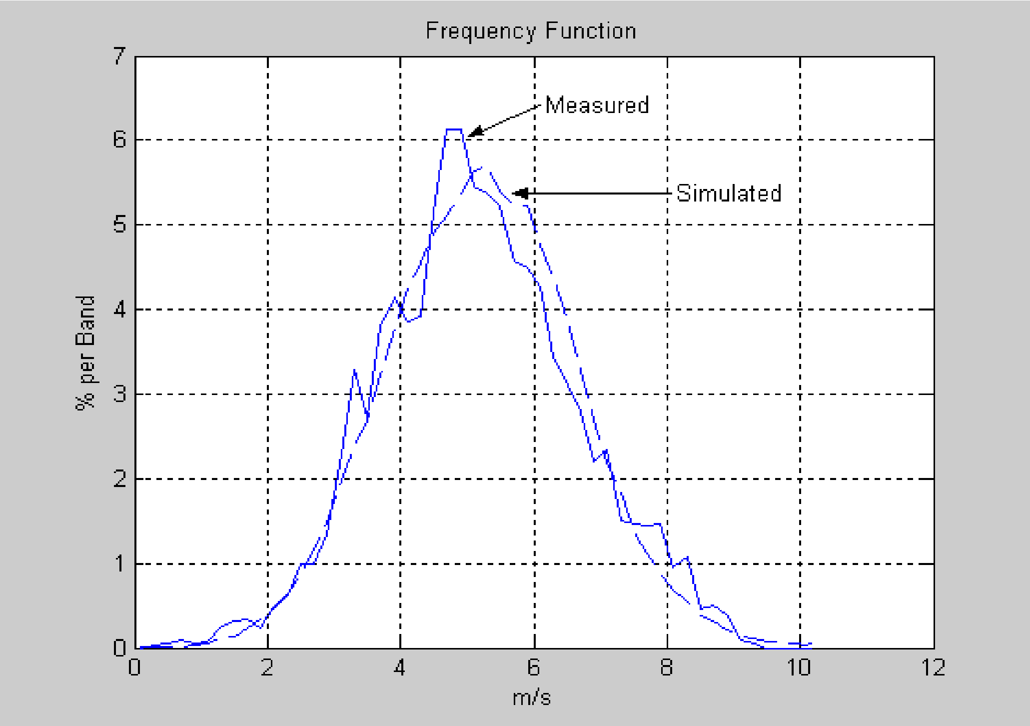

Figure 31 Frequency Function vs Wind Rate Band (see Figure 14). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

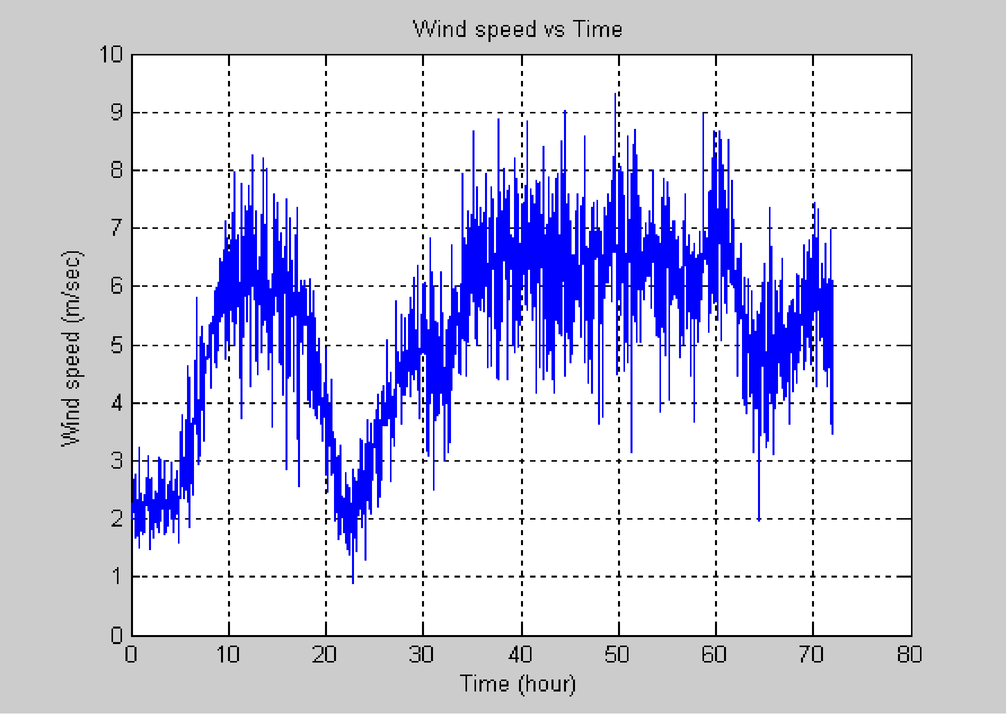

Figure 32 Simulated wind speed with nominal model parameters according to Table 3 and Table 4. Period 2.

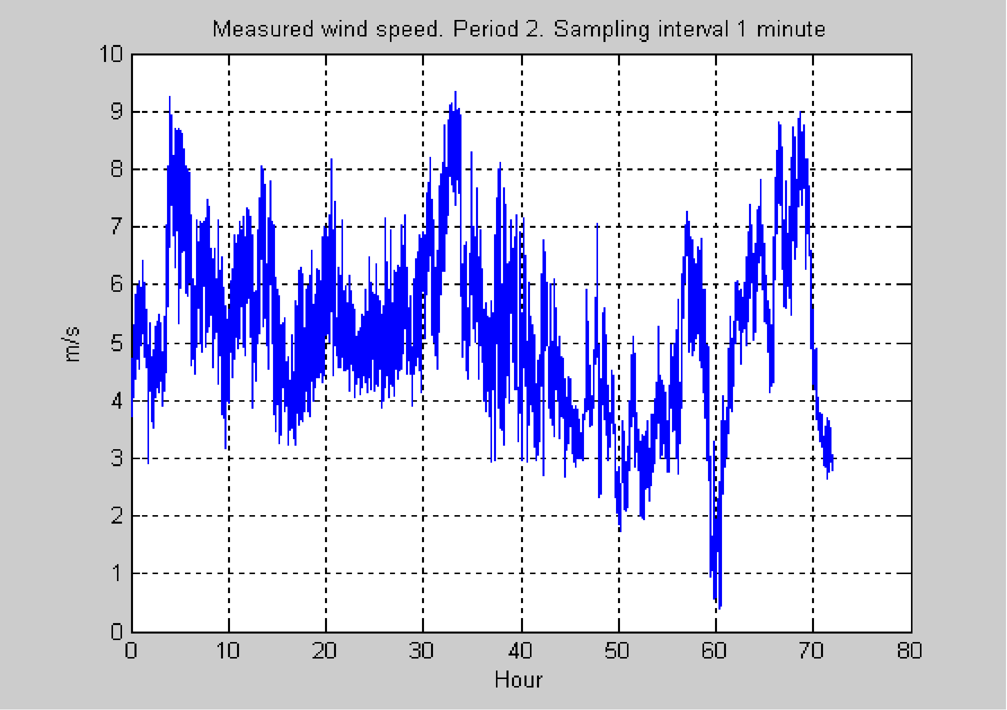

Figure 33 Measured wind speed. Period 2

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ \mathrm{Re}sult}{Measurement\ \mathrm{Re}sult}$
A (C, Turbulence and Turbulence variation nominal)	5.00	0.6468
	5.80 (nominal)	**1.0169**
	6.60	1.5680
C (A, Turbulence and Turbulence variation nominal)	3.00	1.0764
	3.60 (nominal)	**1.0169**
	4.20	1.0342
Turbulence (C, A and Turbulence variation nominal)	5 %	0.9863
	10 %	1.0219
	15 % (nominal)	**1.0169**
	20 %	1.0635
	25 %	1.0817
Turbulence variation (C, A and Turbulence nominal)	**(3,1)** (nominal)	**1.0169**
	(5,2)	1.0262
	(10,3)	1.0214

Table 7 Relative Mean Energy vs variation of some parameters

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
5.2	5.2	1.5	1.4	9.3	10.2	0.4	1.3

Table 8 Statistical parameters regarding wind rate. Measurements vs simulations

4.3 Measuring period 3

Date: 9 – 11 June 2007 (72 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 34 - Figure 41 and in Table 9 and Table 10 the comparisons are presented.

Comments regarding figures and tables:

Figure 34 - Figure 37 The graphs give the correlation between the *Energy Bands* and corresponding wind rates. The following model parameters have been altered:

- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 3.30 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 2.40 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 25 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)[*)] gives the best adaption to the measurement result.

Figure 38 The graphs give the correlation between the *Energy Bands* and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). Simulation with nominal parameters is compared with measurement result.

Figure 39 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific *Wind rate Bands* (defined by wind rates) and the *Wind rate Bands* in question. (Frequency function vs wind rate band).
See Figure 14 and Equation 19. The figure illustrates 52 *Wind rate Bands*, separated with 0.2 m/s. The equation defines the correlation between *Wind rate Bands* and *Wind rates*. Simulation with nominal parameters is compared with measurement result.

Figure 40 and Figure 41 The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 3.

Table 9 lists the resulting *Quotient of Relative Mean Energy* between simulation and measurement during period 3. As can bee noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 10 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement result.

*) mean value: 3, standarddeviation: 1

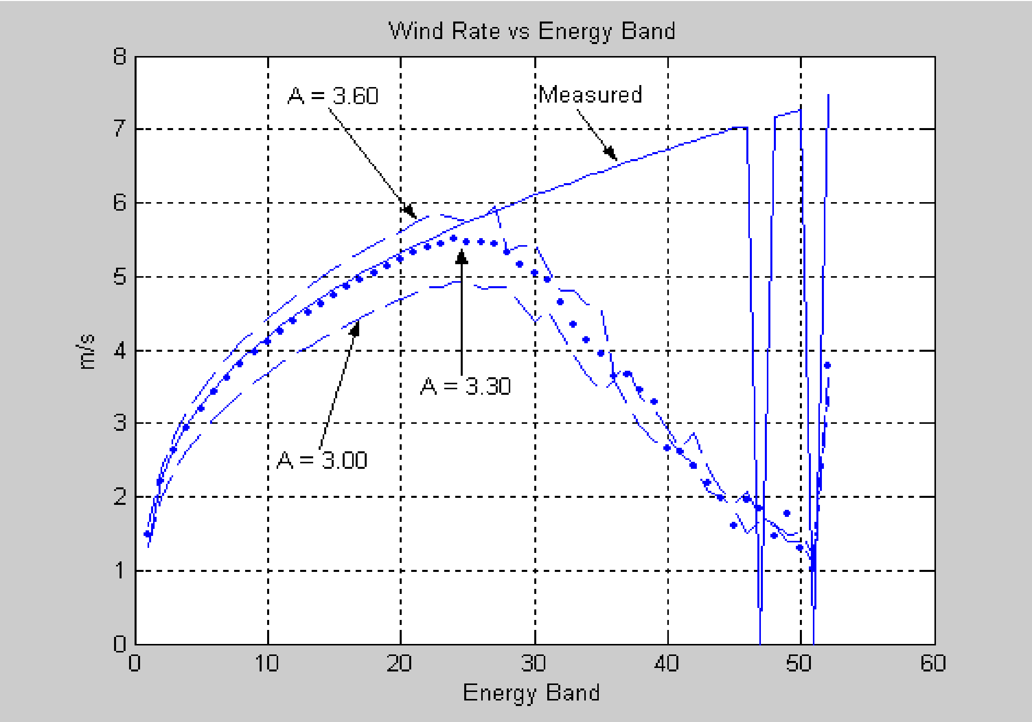

Figure 34 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

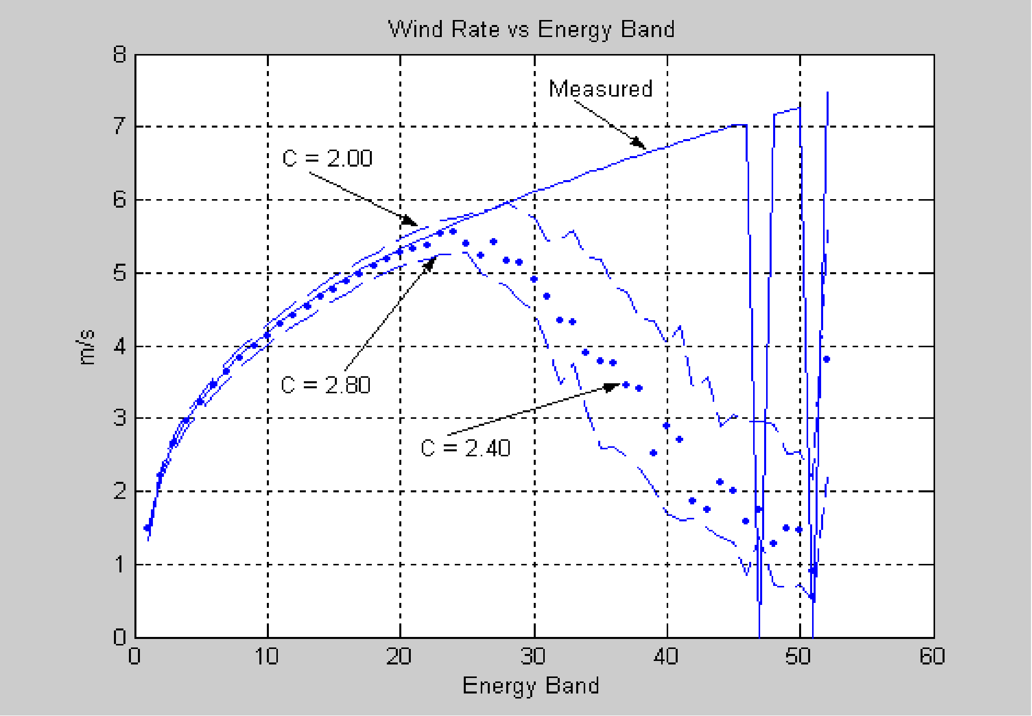

Figure 35 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

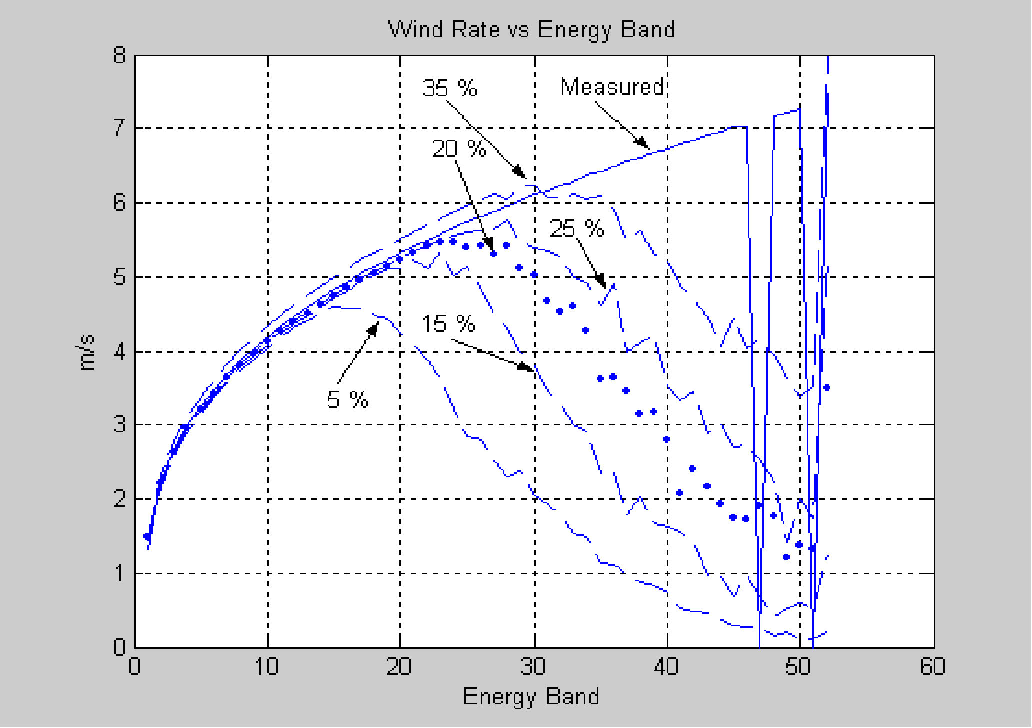

Figure 36 Wind rate vs Energy Band with altering Turbulence level. (A,C, and Turbulence variation are fixed nominal)

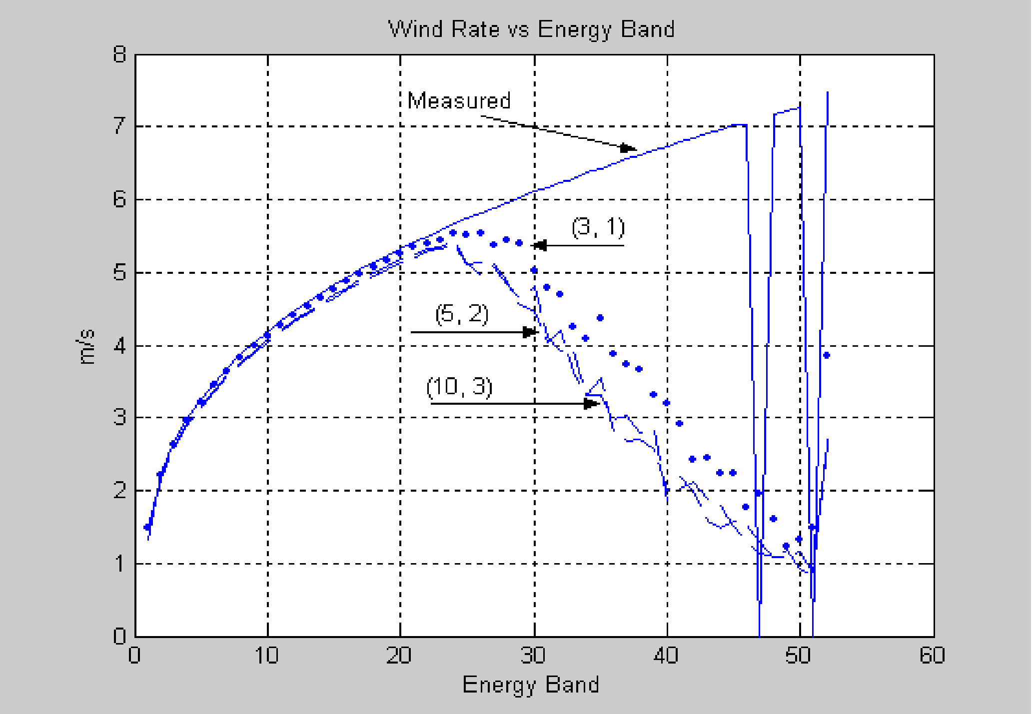

Figure 37 Wind rate vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

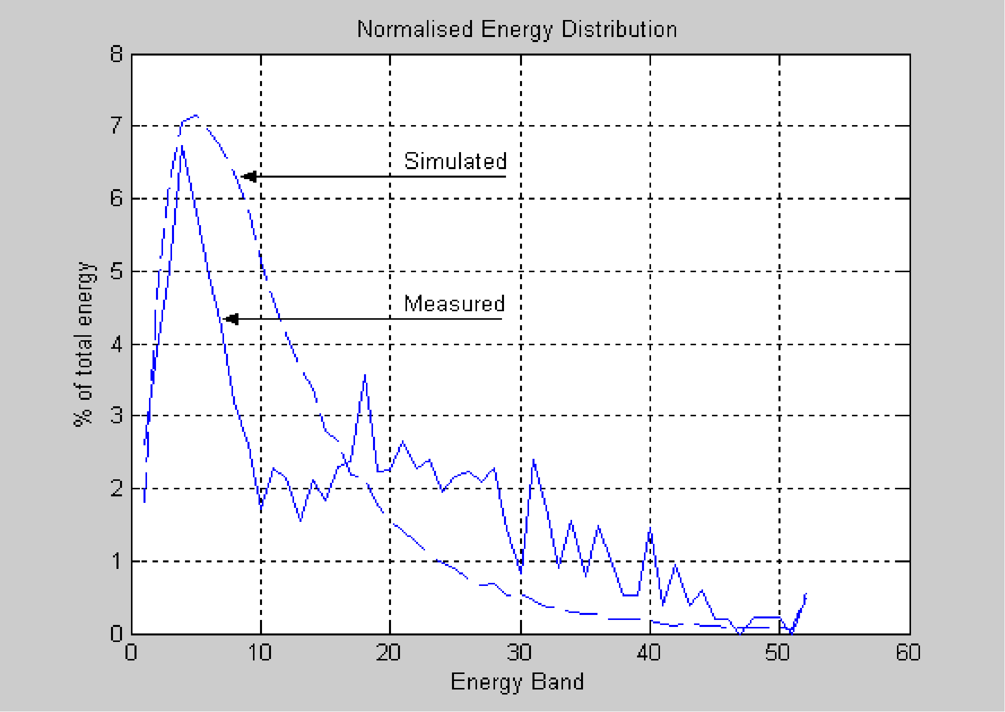

Figure 38 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

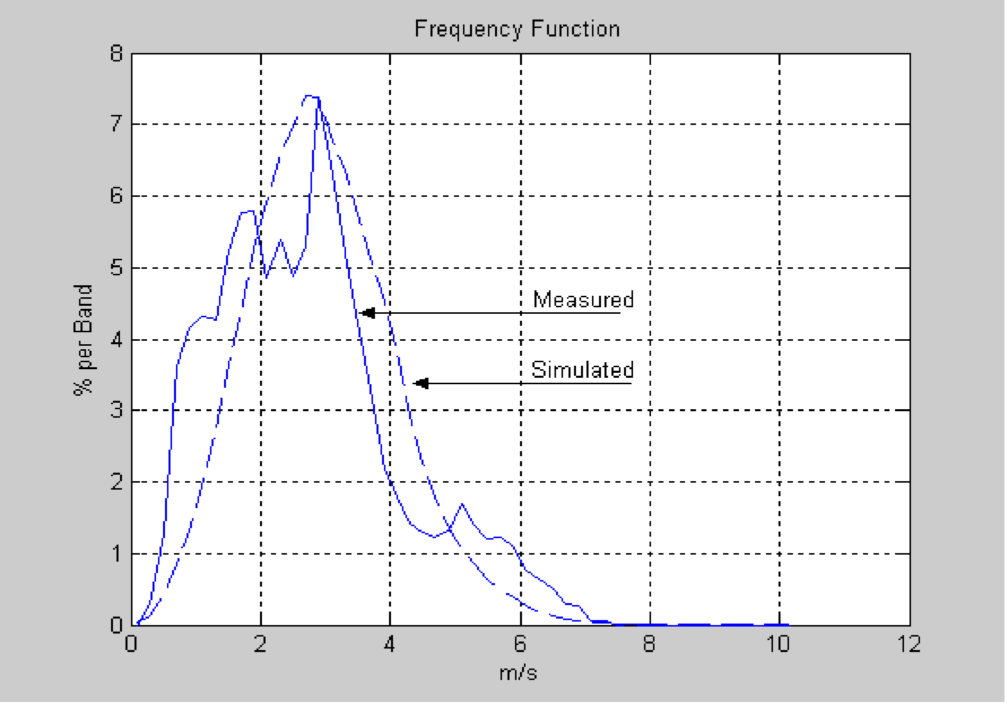

Figure 39 Frequency Function vs Wind Rate Band (see Figure 14). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

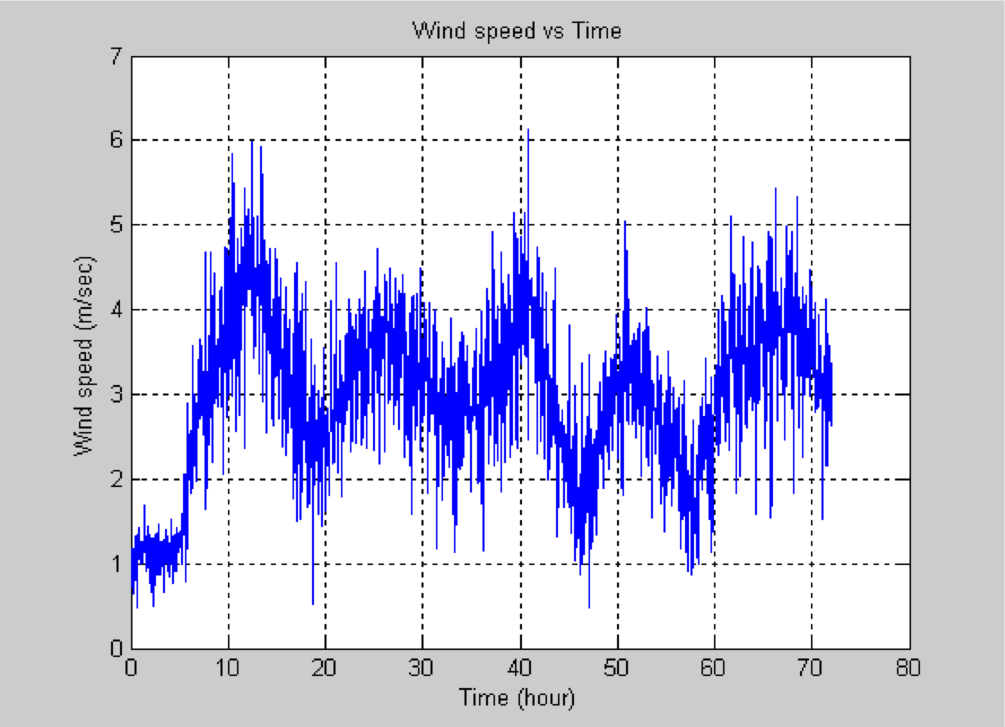

Figure 40 Simulated wind speed with nominal model parameters according to Table 3 and Table 4. Period 3.

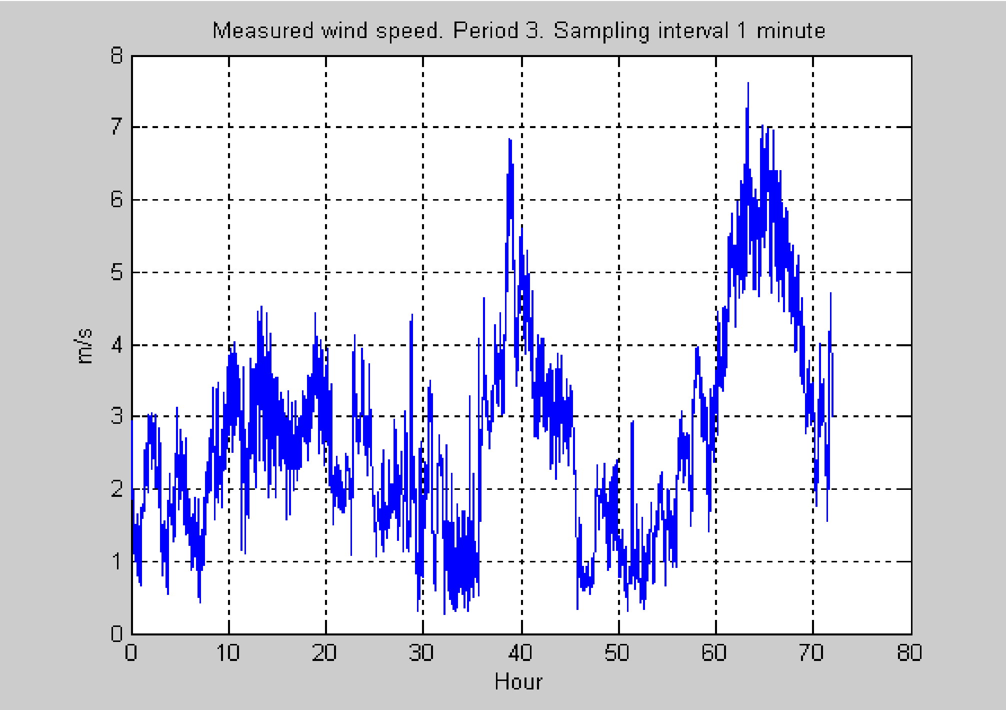

Figure 41 Measured wind speed. Period 3

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ Result}{Measurement\ Result}$
A (C, Turbulence and Turbulence variation nominal)	3.00	0.7123
	3.30 (nominal)	**<u>0.9962</u>**
	3.60	1.2358
C (A, Turbulence and Turbulence variation nominal)	2.00	1.1330
	2.40 (nominal)	**<u>0.9962</u>**
	2.80	0.9099
Turbulence (C, A and Turbulence variation nominal)	5 %	0.9398
	15 %	0.9674
	20 % (nominal)	**<u>0.9962</u>**
	25 %	1.0033
	35 %	1.1718
Turbulence variation (C, A and Turbulence nominal)	(3,1) (nominal)	**<u>0.9962</u>**
	(5,2)	0.9341
	(10,3)	0.9607

Table 9 Relative Mean Energy vs variation of some parameters

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
2.7	2.9	1.4	1.1	7.6	7.3	0.3	0.2

Table 10 Statistical parameters regarding wind rate. Measurements vs simulations with nominal parameters

4.4 Measuring period 4

Date: 17 – 21 June 2007 (120 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 42 - Figure 51 and in Table 11 and Table 12 the comparisons are presented.

Comments regarding figures and tables:

Figure 42 - Figure 46 The graphs give the correlation between the *Energy Bands* and corresponding wind rates. The following model parameters have been altered:

- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 3.80 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 2.50 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 25 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)[*)] gives the best adaption to the measurement result.

Figure 47 - Figure 48 The graphs give the correlation between the *Energy Bands* and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal) have been altered. C = 2.50 gives the best adaption to the measurement result.

Figure 49 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific *Wind rate Bands* (defined by wind rates) and the *Wind rate Bands* in question. (Frequency function vs wind rate band).
See Figure 14 and Equation 19. The figure illustrates 52 *Wind rate Bands*, separated with 0.2 m/s. The equation defines the correlation between *Wind rate Bands* and *Wind rates*. Simulation with nominal parameters is compared with measurement result.

Figure 50 - Figure 51 The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 4.

Table 11 lists the resulting *Quotient of Relative Mean Energy* between simulation and measurement during period 4. As can bee noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 12 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement result.

*) mean value: 3, standarddeviation: 1

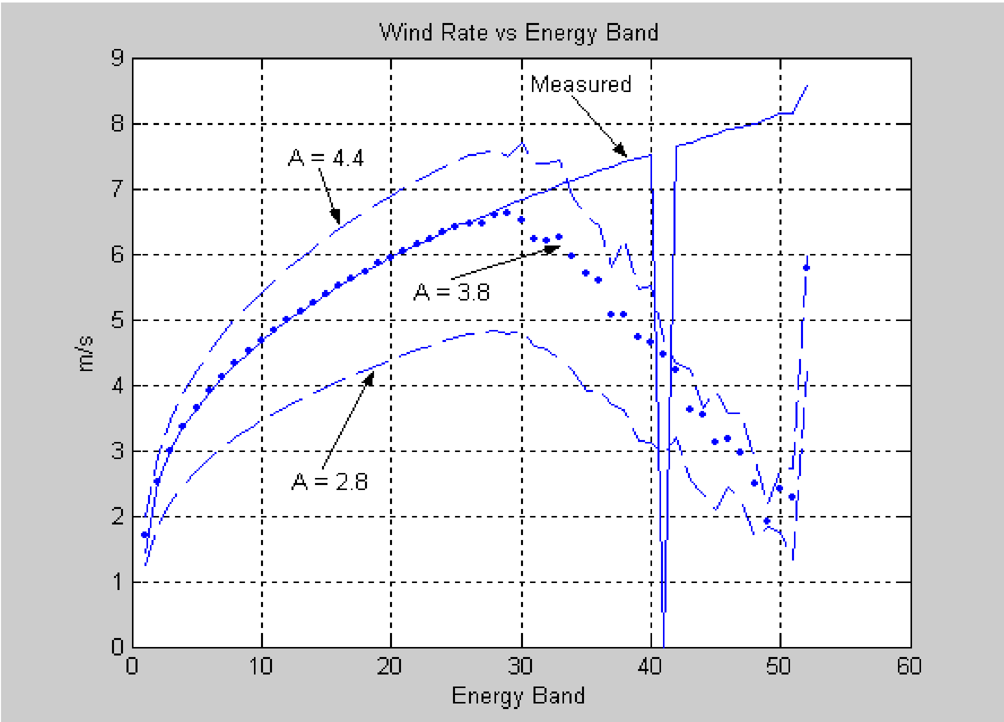

Figure 42 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

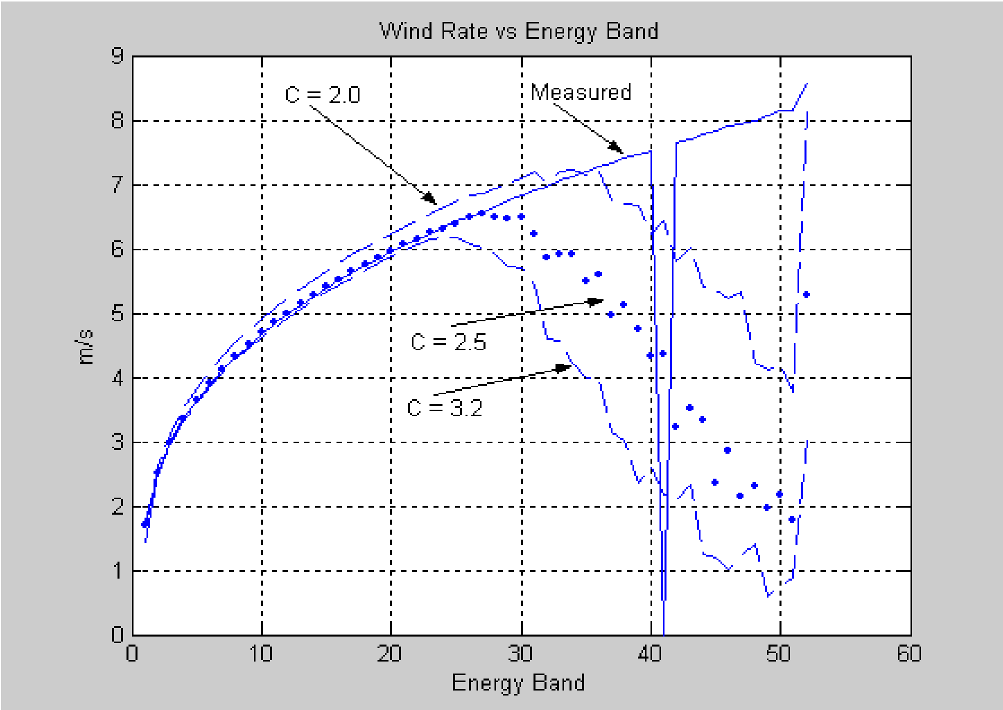

Figure 43 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

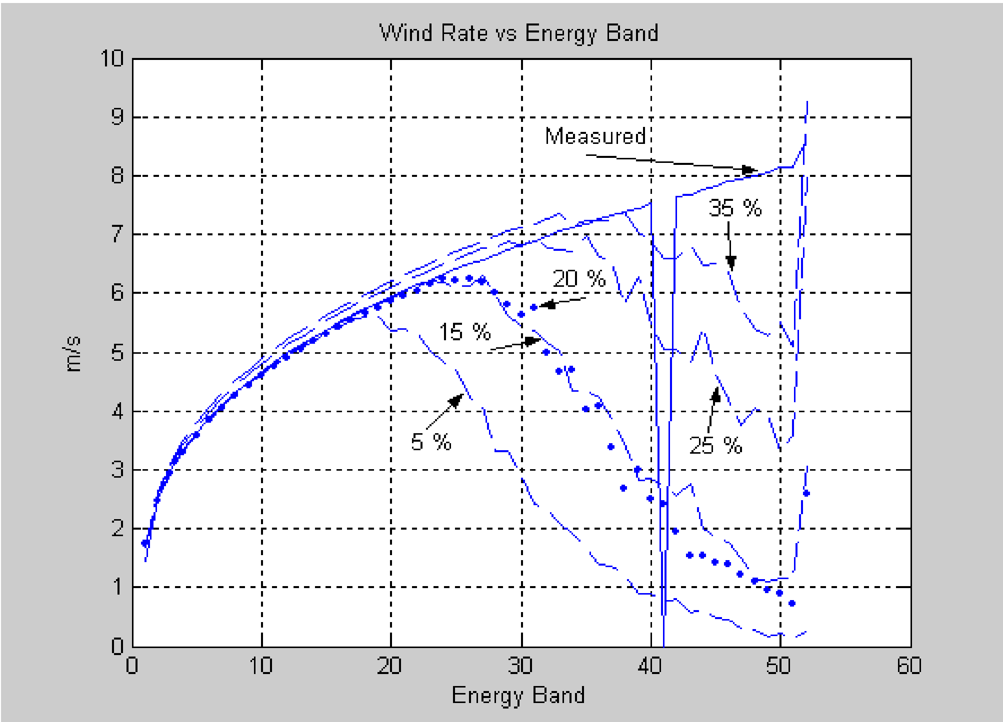

Figure 44 Wind rate vs Energy Band with altering Turbulence. (A, C, and Turbulence variation are fixed nominal)

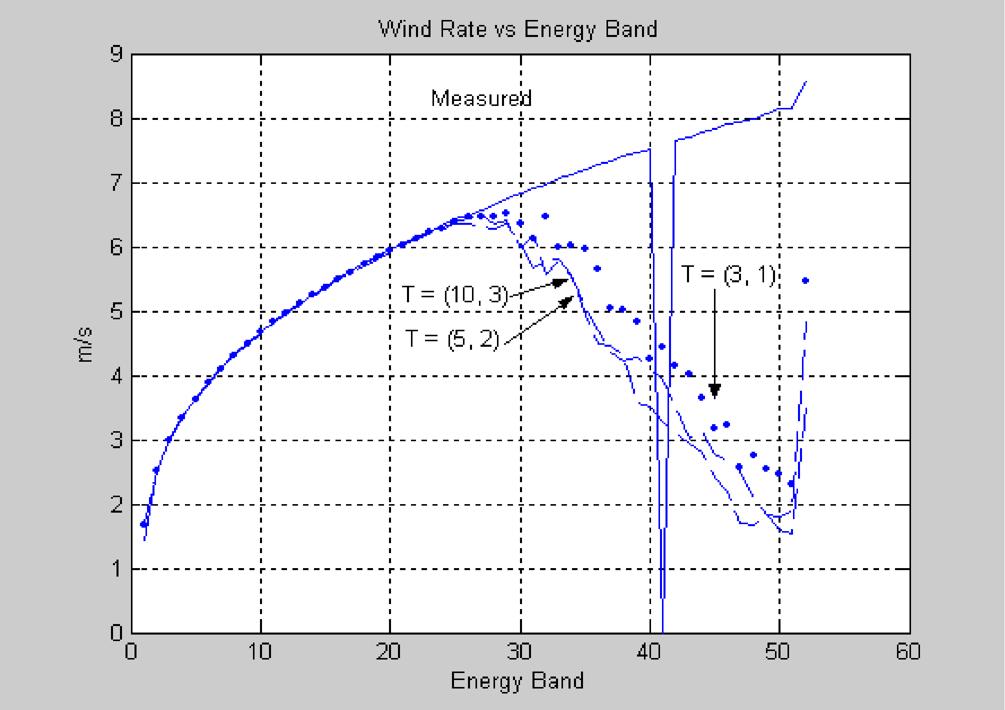

Figure 45 Wind rate vs Energy Band with altering Turbulence variation. (A, C, Turbulence are fixed nominal)

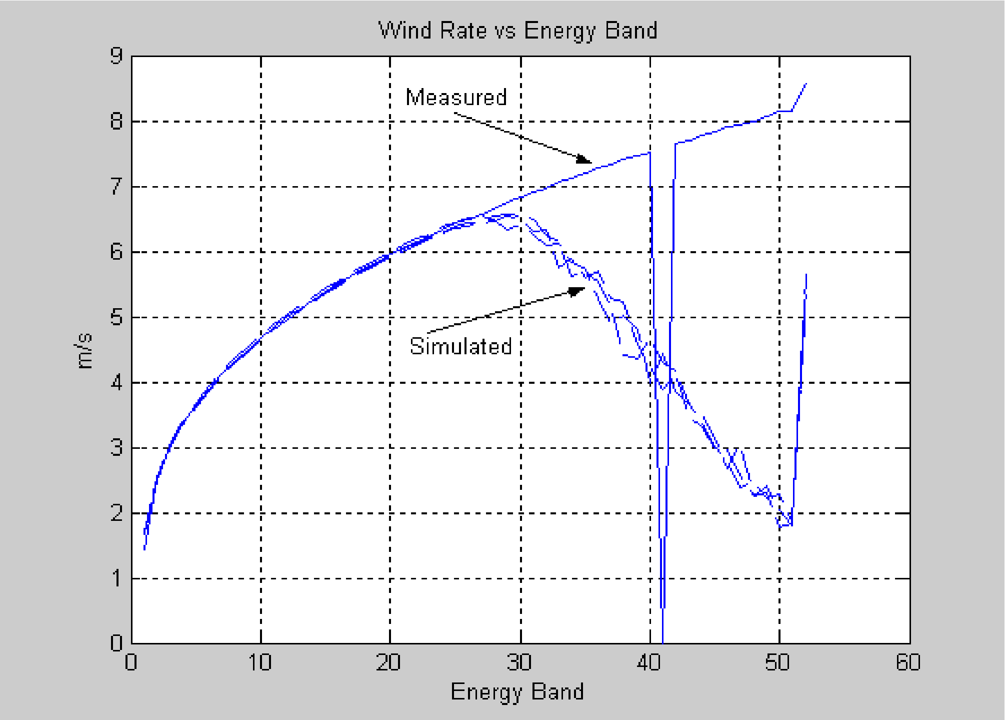

Figure 46 Wind rate vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation). 3 separated simulation sequences are compared

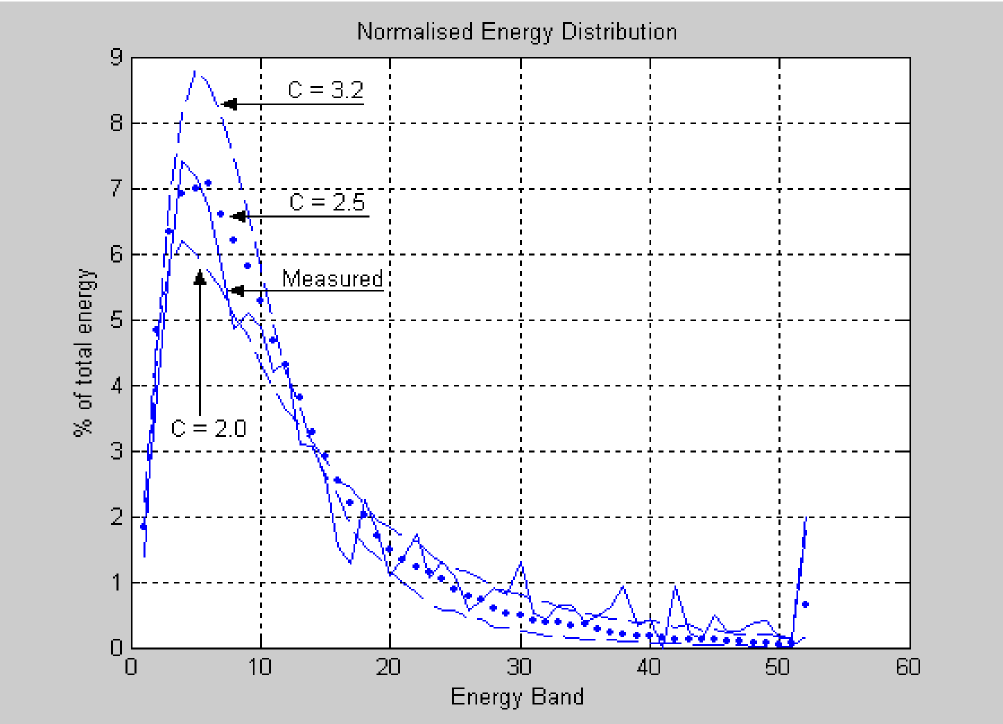

Figure 47 Normalised Energy Distribution vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

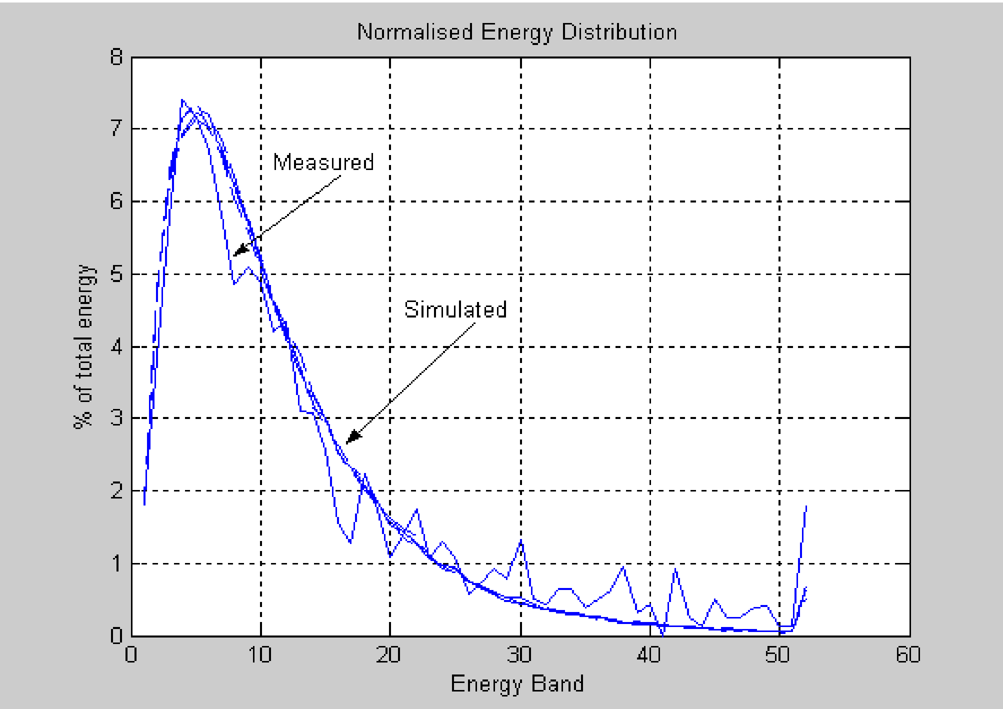

Figure 48 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation). 3 separated simulation sequences are compared

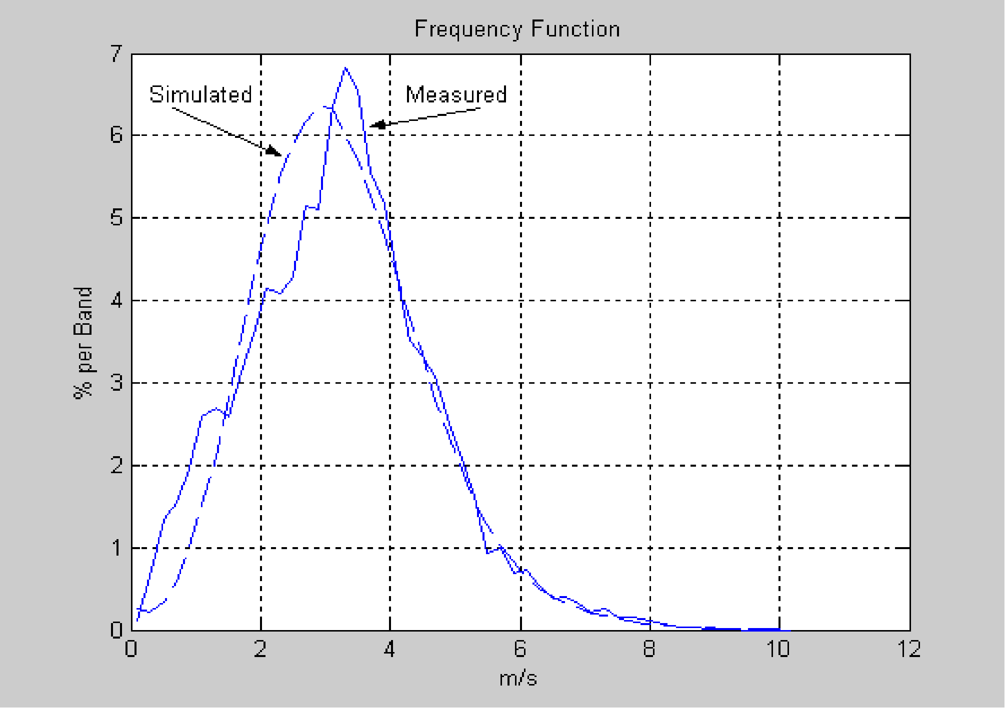

Figure 49 Frequency Function vs Wind Rate Band (see Figure 14). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

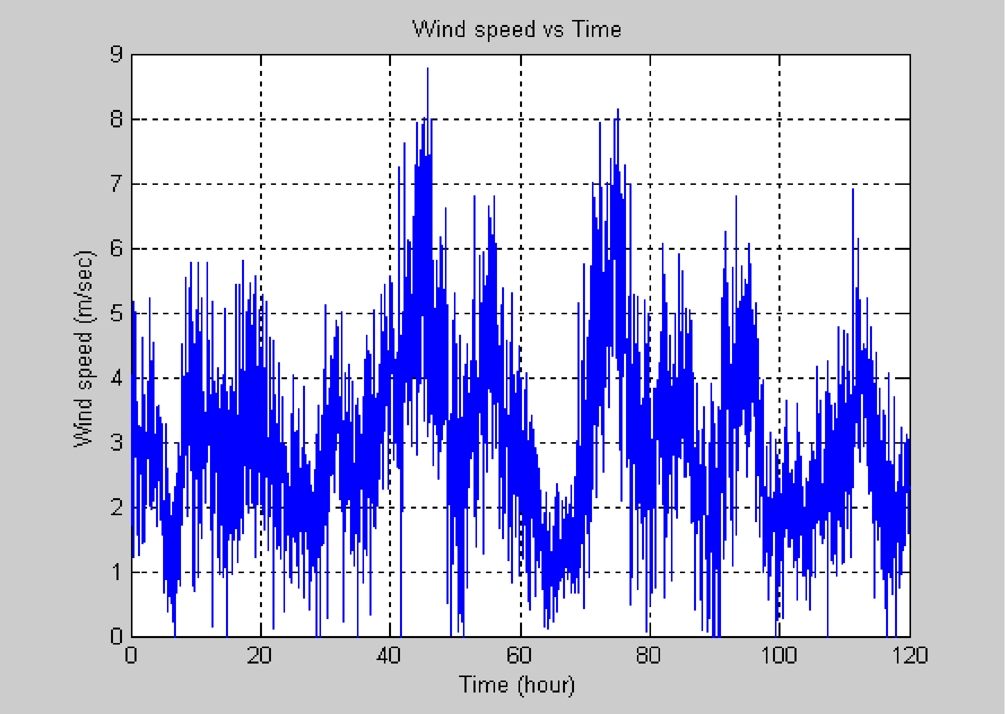

Figure 50 Simulated wind speed with nominal model parameters according to Table 3 and Table 4. Period 4.

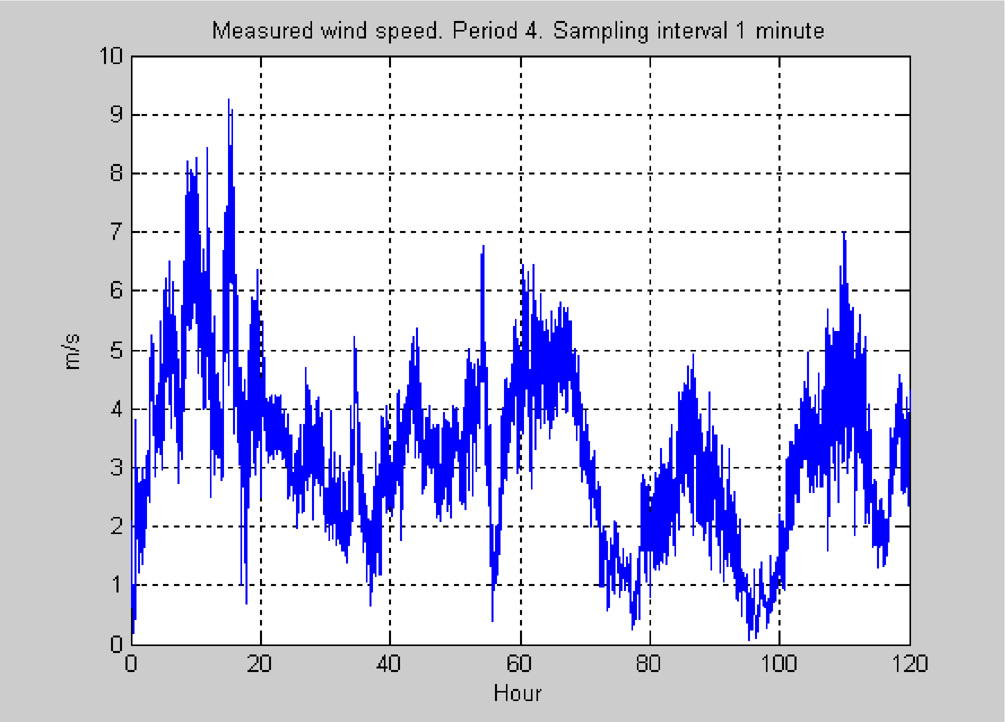

Figure 51 Measured wind speed. Period 4

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ Result}{Measurement\ Result}$
A (C, Turbulence and Turbulence variation nominal)	2.80	0.4111
	3.80 (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	4.40	1.5980
C (A, Turbulence and Turbulence variation nominal)	2.00	1.1971
	2.50 (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	3.20	0.9766
Turbulence (C, A and Turbulence variation nominal)	5 %	0.9875
	15 %	1.0149
	20 % (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	25 %	1.1075
	35 %	1.1687
Turbulence variation (C, A and Turbulence nominal)	(3,1) (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	(5,2)	1.0310
	(10,3)	1.0101

Table 11 Relative Mean Energy vs variation of some parameters

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
3.2	3.4 (3.4, 3.4)	1.4	1.2 (1.2, 1.2)	9.2	8.6 (8.5, 8.7)	0.1	0.1 (0.2, 0.1)

Table 12 Statistical parameters regarding wind rate. Measurements vs simulations with nominal parameters

5 CONCLUSION

To adapt the model parameters to the measurement data the following principle is recommened:

- *Sim_step_W_My*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. In the previous examples according to period 1 – 4, *Sim_step_W_My* consistently has been assigned to the value *300*.

- *Sim_step_W_Sigma*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. In the previous examples according to period 1 – 4, *Sim_step_W_Sigma* consistently has been assigned to the value *100*.

- *Sim_step_T_My*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. See Figure 18, Figure 26, Figure 29, Figure 37 and Figure 45 and Table 5, Table 7, Table 9 and Table 11. In the previous examples according to period 1 – 4, *Sim_step_T_My* consistently has been assigned to the value *3*.

- *Sim_step_T_Sigma*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. See Figure 18, Figure 26, Figure 29, Figure 37 and Figure 45 and Table 5, Table 7, Table 9 and Table 11. In the previous examples according to period 1 – 4, *Sim_step_T_Sigma* consistently has been assigned to the value *1*.

- *Level_T_Sigma_proc*. The parameter is estimated by comparing measurements with simulations in the following routines:

a) The graphs that give the correlation between the *Wind rate vs Energy Band* (see Figure 17, Figure 25, Figure 36 and Figure 44).

b) The graphs that give the correlation between the *Normalised Energy Distribution vs Energy Band* (see Figure 28). The present judgement is that this point can bee canseled if point a) is realized.

c) *Relative Mean Energy* (see Table 5, Table 7, Table 9 and Table 11)

d) The statistic parameters *meanvalue*, *standarddeviation*, *maximum* and *minimum* (see Table 6, Table 8, Table 10 and Table 12)

- Weibull parameter *A*. The parameter is estimated by comparing measurements with simulations in the following routines:

a) The graphs that give the correlation between the *Wind rate vs Energy Band* (see Figure 15, Figure 23, Figure 34 and Figure 42)

c) *Relative Mean Energy* (see Table 5, Table 7, Table 9 and Table 11)

d) The statistic parameters *meanvalue*, *standarddeviation*, *maximum* and *minimum* (see Table 6, Table 8, Table 10 and Table 12)

- Weibull parameter *C*. The parameter is estimated by comparing measurements with simulations in the following routines:

a) The graphs that give the correlation between the *Wind rate vs Energy Band* (see Figure 16, Figure 24, Figure 35 and Figure 43). The present judgement is that this point can bee canseled if point b) is realized.

b) The graphs that give the correlation between the the *Normalised Energy Distribution vs Energy Band* (see Figure 27 and Figure 47).

c) *Relative Mean Energy* (see Table 5, Table 7, Table 9 and Table 11)

d) The statistic parameters *meanvalue*, *standarddeviation*, *maximum* and *minimum* (see Table 6, Table 8, Table 10 and Table 12)

The present judgement is that it is sufficient only to realize point b) and point c). Point a) and point d) can bee canseled without any effect on the quality of the result. However it is interesting to have a check on the statistic parameters *meanvalue*, *standarddeviation*, *maximum* and *minimum*.

Table 13 gives a summary of the estimation routines

Model parameter	Estimation method
Sim_step_W_My	Visual comparison between the measurement and simulation regarding the period of time
Sim_step_W_Sigma	-“-
Sim_step_T_My	-“-
Sim_step_T_Sigma	-“-
Level_T_Sigma_proc	Comparison between the measurement and simulation regarding: - *Wind rate vs Energy Band* - (*Normalised Energy Distribution vs Energy Band*) - *Relative Mean Energy* - *Meanvalue, standarddeviation, maximum and minimum*
A	Comparison between the measurement and simulation regarding: - *Wind rate vs Energy Band* - *Relative Mean Energy* - *Meanvalue, standarddeviation, maximum and minimum*
C	Comparison between the measurement and simulation regarding: - (*Wind rate vs Energy Band*) - *Normalised Energy Distribution vs Energy Band* - *Relative Mean Energy* - *Meanvalue, standarddeviation, maximum and minimum*

Table 13 Summary of the parameter estimation routines

6 FUTURE WORK

As future work the following is suggested:

- analysis based on measurements representing strong varying whether conditions (e.g. wind rates from a few metres per second up to at least 20 metres per second)

- a deeper teorethical analysis regarding different statistical relations

7 REFERENCES

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