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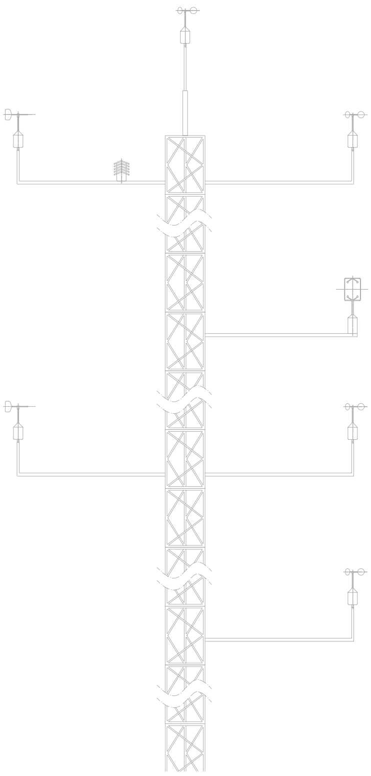
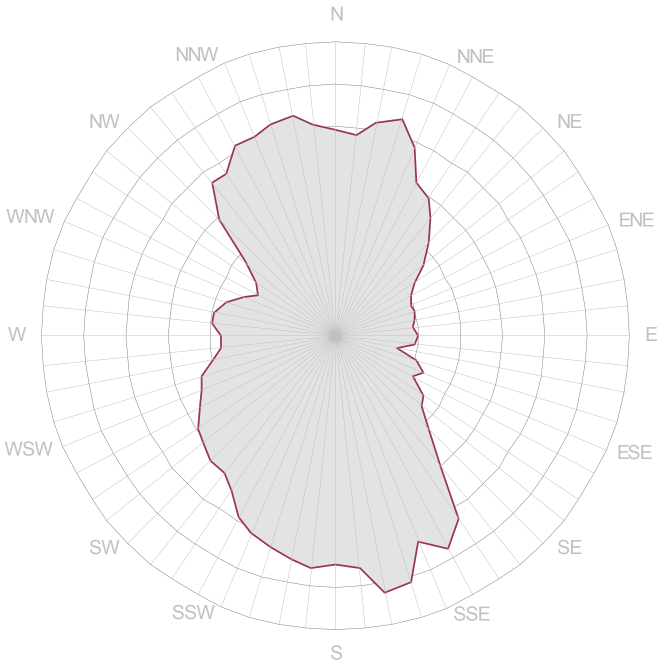
A wind data analysis tool

WindRose

User's Guide





Document version: 8.1 *Excel COM+ Add-In* version: 3.88 Analysis *DLL* version: 5.89

Table of Contents

INTRODUCTION

WindRose is a software tool dedicated to the analysis of wind characteristics (speed, direction, turbulence, temperature). It is not a standalone program, but an *Add-In* to the Microsoft Excel® 2000/XP/2003/2007, for the Windows 9x/ME/NT4/2000/XP/Vista/7 operating systems. The analysis results are stored graphically and numerically into spreadsheets, which can be further used as ordinary Excel files.

The program is designed to provide all the results of the data analysis, in a customisable form to meet any particular needs. Thus, the user can rearrange all the graphs, resize them, change their colours, copy or link them to other sheets or programs (i.e.: embedded links to Microsoft Word® document), create new tables using the numerical results, etc.

Data analysis complies with the requirements imposed by the IEC and MEASNET standards.

Main features

- It performs complete statistical analysis of the wind data, including Weibull distribution constants (per direction sector and global), turbulence intensity evaluation and polar plots (wind roses) of the time and energy distribution of the wind.

- It correlates data from two sites calculating correlation coefficients globally and per ranges of wind speed and direction. As a result, it provides the predicted time-series for the missing data of a site, based on the other site's complete set of data (MCP method).

- Where multiple anemometers and/or wind vanes are present, the vertical wind shear is calculated (per wind speed and per direction sector). Thus, the extrapolation of the wind speed at higher heights (ie: hub height of a wind turbine) is performed more accurately.

- A dozen of power-curves from a variety of wind turbines are included, providing a good estimate of the expected energy production.

- It has a user configurable time step (10 minutes, 1 hour, etc) and it is able to analyse huge data sets (limited only by the available computer memory).

- In case of measurements with systematic errors, a linear correction can be applied for all the measured quantities and separately for each file.

- It includes 3 methods for the air-density correction (due to the site elevation height and to the temperature), which is critical for the correct calculation of the wind energy.

- It produces monthly charts and tables with the per hour variation of wind speed, wind direction, expected wind turbine's power, temperature and solar radiation.

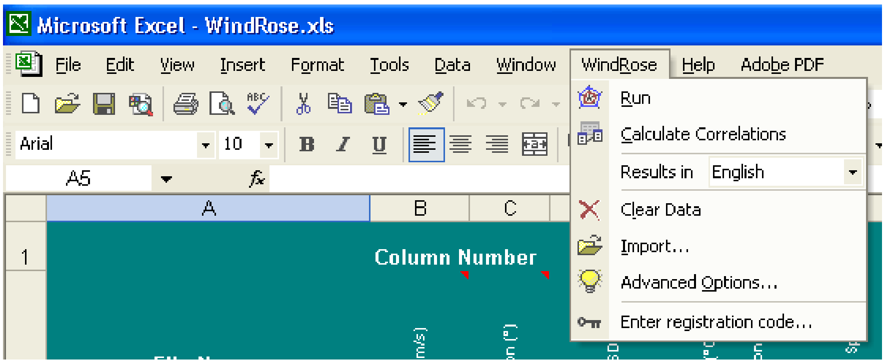
How it works

WindRose reads ASCII files containing columns of data, an output format supported by the majority of data-loggers. Five[1] columns of data are necessary for the program to run: wind speed, wind direction, standard deviation of the wind speed, time and date. Several formats are supported when dealing with date and time. Whenever temperature atm. pressure, humidity, solar radiation, flow inclination are recorded, the appropriate analysis is performed.

[1] If the wind speed's standard deviation is not recorded, the program can still run, using the following trick: provide the same column numbers for both U (wind speed) and Usdv and then ignore the Turbulence Intensity results (which will be constant to: 100%).

INSTALLATION

Assuming that Microsoft Excel is properly installed, *WindRose* can be installed using the SETUP.EXE program. Administration privileges are required in Windows NT4/2000/XP. At the end of the installation, the *WindRose* option is added in the main menu of the Excel (Figure 1). By opening the *WindRose.XLS* file (default location: `c:\Program Files\WindRose`), you are ready to run the program for the first time (see below *RUNNING THE PROGRAM*).



Running WindRose within Excel.

Digital Signature

Microsoft Excel has security levels that allow users to run macros based on whether or not they are digitally signed by a trusted macro developer. The *WindRose.XLS* file includes some macros and has a digital signature named *WindRose*. The first time that the *WindRose.XLS* file is opened, the user is asked whether or not the macros should be enabled. Answer *yes* so that *WindRose* runs properly and never asked in the future the same question.

If you are not allowed to open the *WindRose.XLS* file with the included macros enabled (might happen if the Security Level of Excel is set to: *High*), then consult the Appendix: *INSTALLATION ISSUES.*

RUNNING THE PROGRAM

Running the program for the first time

Three sample data files (*ST-FLASH.TXT, NOMAD.TXT* and *GenASCII.TXT*) containing wind data are included in the package to facilitate the first run of the program. Moreover, the `Input` worksheet contains already, all the required information to run the wind data analysis for the specific data files. All the user has to do is, to select from the Excel Main Menu, "*WindRose*" and then, "*Run*" [2]. The status bar of the Excel should then display the different steps of the program's execution[3]. At the end, the results of the analysis are stored in forms of graphs and/or tables into the different worksheets.

Before calculating the correlations/predictions between 2 sites, *WindRose* has to be run twice, once per each site.

The *WindRose* Excel workbook is composed by the following 24 worksheets:

1. *Input*	9. *UhourT*	17. *DIRhourG*
2. *PowerCurve*	10. *TimeCharts*	18. *DIRhourT*
3. *Results*	11. *3D*	19. *TempG*
4. *WindCorr*	12. *12diurnal*	20. *TempT*
5. *Tables*	13. *12pie*	21. *SradG*
6. *Weibull*	14. *BarCharts*	22. *SradT*
7. *Upolar*	15. *WtprodG*	23. *TempData*
8. *UhourG*	16. *WtprodT*	24. *Air-Density*

Two worksheets (`Input` and `PowerCurve`) are used for defining all the necessary parameters to run the program. The remaining worksheets are used for presenting graphically and numerically the results of the analysis. The content of all the worksheets is explained in detail in the following paragraphs.

Note

- When working with the original *WindRose.XLS*, keep it unchanged for future use, by saving it at the end of the analysis (using the *Save As…* option) with another name.

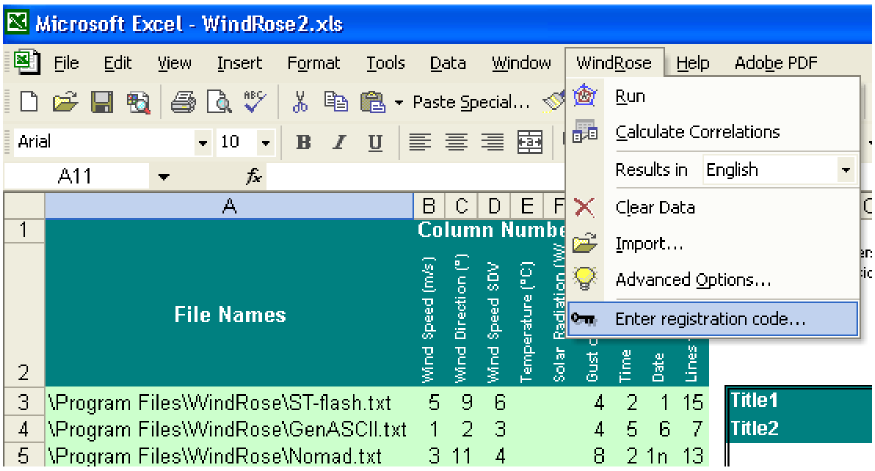
---

[2] If the default program path: `c:\Program Files\WindRose` was changed during the installation, then modify accordingly the paths of the 3 provided sample files in the `Input` sheet.

[3] During the program execution and under certain circumstances, the PC may not respond for a few seconds.

Demo version Registration

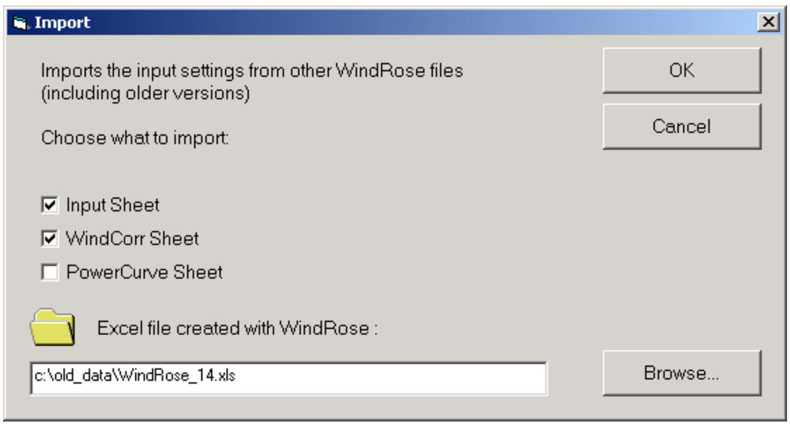
The demo version of the *WindRose* (for unregistered users) incorporates all the features of the full version, but is limited to analysing measured data that do not exceed 31 days. Registered users are given a code, which is entered using the *WindRose* menu within Excel.



If the PC's OS is Windows Vista, then before entering the code, turn off the *User Account Control* (Control Panel, Security Center) and turn it back on afterwards.

Import OLD WindRose.XLS files

Excel files created with older versions of *WindRose*, can be imported using the *"Import…"* option of the *WindRose* menu (see figure below). Regarding older files, this version of WINDROSE.XLS has some new input parameters and graphs, therefore some graphs and tables may not display correctly.



THE INPUT WORKSHEETS

Input

Four tables compose this worksheet, which deals with the input data and the necessary parameters required by the program.

The **first table** contains the names of the ASCII files to be read together with the column numbers of the requested quantities (wind speed, direction etc). The number of the lines to skip in the beginning of each file, containing blank lines or comments is also given here. **Multiple data files can be specified by using wildcards (*, ?) in their names.** If the order of the files is not the chronological one (from older to newer data), then sorting of data is performed automatically without any user action. However, additional memory is needed for that. Some of the columns of the ASCII data file can be assigned as *control signals*, enabling thus data filtering depending on *e.g.*: the data logger's battery level, the rain, the signal quality of Lidars (CNR for Windcube, points in fit for ZephIR), etc. The acceptable range of each control signal can be assigned in WindRose's *Advanced Options…* menu.

Note that wildcards (* and ?) are accepted to specify multiple files

File Names	Column Number: Wind Speed (m/s)	Wind Direction (°)	Wind Speed SDV (m/s)	Temperature (°C)	Solar Radiation (W/m2)	Gust of Wind Speed (m/s)	Atm. Pressure (hPa)	Rel.Humidity	Flow Inclination (deg)	El. Power (kW)	RPM	Control Signal A	Control Signal B	Control Signal C	Time	Date	Lines to skip
c:\site1\st09*.*	5;9;13	17;21	6;10;14	25		4;8;12	29								2	1	15
c:\site1\processed1.txt	1;2;3	4;5	6;7;8	9		10;11;12	13								14	15	

File names and column numbers (sheet `Input`).

Delimiting characters (within the ASCII data files)

It is expected that ASCII files contain some comment lines in the beginning, followed by at least 5 columns of data. The accepted characters delimiting (separating) the columns are the following:

- The space
- The comma (,)
- The semicolon (;)
- The 2 parentheses
- The tab
- The double quotation marks (")

Time format

WindRose accepts as time format, when reading ASCII files, the following forms:

`hh:mm:ss , hh.mm.ss , hhmmss , hh:mm , hh.mm , hhmm`

Note that, if none of the delimiting characters: `: .` are present and 5-6 digits are found then, the last two represent the seconds, the middle two the minutes and the first one(s) the hour. If 3-4 digits are found then, the last two represent the minutes and the first one(s) the hour of the day. Finally, if just 1-2 digits are found, then depending on the time step they are considered either as minutes, if the time step < 1h (i.e.: `5` is taken as `00:00:05`), or as the hour of the day, if the time step ≥ 1h (i.e.: `5` is taken as `05:00:00`).

Other custom formats i.e.: the 12-hour form using `am` and `pm` (i.e.: 1:50pm) and the French-style `h` (i.e.: 13h50) can be supported on demand.

Finally, there are cases where time comes in the form of incremental steps from the beginning of the day. Thus, the time column is filled with integers increasing from 1 to 144 (time step=10min) or from 1 to 1440 (time step=1min) etc. In this case we add the character *s* right after the column number. For example if the time column was the 9th we put `9s`.

Date format

WindRose defaults to the European date format, but also accepts other date formats. If the date has one of the following (European) formats, then it is directly read.

`ddmmyy , ddmmyyyy , d/m/yy , dd/mm/yyyy , d.m.yy , dd.mm.yyyy , d-m-yy , dd-mm-yyyy`

The acceptable delimiting characters for the date format are: `/ . -`.

If the American format is used (`mm/dd/yy`, `mmddyyyy`, etc) then, right after the column number of the date, we put the character *u* i.e.: for the 10th column we write `10u`.

If the "international" date format is used (`yymmdd`, `yyyy.mm.dd`, etc) then after the column number of the date, we put the character *i* i.e.: for the 10th column we write `10i`.

Measurements data coming from the `NOMAD data logger` use another date format. I.e.: for the 26th September 1998 it is written:

```
Sep 26, 1998
```

When reading such files, the above sequence should be considered as <u>one column</u> (instead of 3). Additionally, right after the column name we put the character *n* i.e.: for the 10^{th} column we write `10n`.

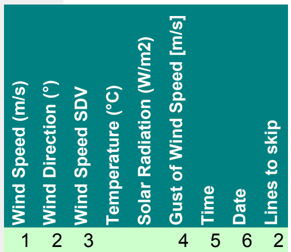
Some models of the `CAMPBELL data loggers` use another particular date format: An integer number is given indicating the number of days elapsed from the beginning of the year. Thus, for the 26^{th} September 1998 it is written:

```
1998, 269
```

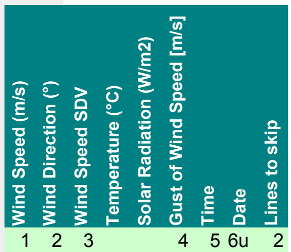
This case is treated by adding the letter *c* right after the date column number i.e.: for the 10^{th} column we write `10c` However, the day-column: **i)** has to be next to the year column (i.e.: 11^{th} in the previous example) **ii)** should not be the file's last one and **iii)** is normally counted when numbering the columns of the ASCII file.

Below, some examples are given showing how the *`Input`* sheet should be filled[4].

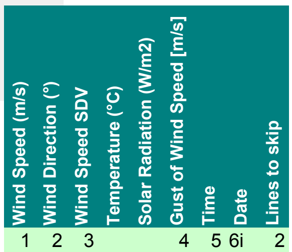
WindSpeed	Dir	Usdv	Gust	Time	Date
14.3	137.6	2.9	22.7	0:7	01/12/00
14.3	144.6	2.8	21.9	0:17:00	1/12/00
13.9	146.5	2.9	21.1	0:27:00	1/12/0
14.1	144.0	2.9	22.7	00:37:00	1-12-2000
13.4	146.6	2.7	21.1	00:47:0	1.12.2000
13.1	144.3	2.6	20.4	0057	1.12.00
12.4	142.1	2.8	20.4	0107	1-12-2000
12.6	140.6	2.5	19.6	0117	1/12/2000
12.8	146.5	3.2	21.9	01.27.00	01122000
12.4	144.1	3.0	21.1	01.37.00	01122000
13.2	147.8	3.0	20.4	1.47.00	01122000
13.3	150.3	3.0	20.4	015700	01122000
12.8	148.3	2.5	21.1	020700	01122000



WindSpeed	Dir	Usdv	Gust	Time	Date
14.3	137.6	2.9	22.7	0:7	12/01/00
14.3	144.6	2.8	21.9	0:17:00	12/1/00
13.9	146.5	2.9	21.1	0:27:00	12/1/0
14.1	144.0	2.9	22.7	00:37:00	12-1-2000
13.4	146.6	2.7	21.1	00:47:0	12.1.2000
13.1	144.3	2.6	20.4	0057	12.1.00
12.4	142.1	2.8	20.4	0107	12-1-2000
12.6	140.6	2.5	19.6	0117	12/1/2000
12.8	146.5	3.2	21.9	1.27.00	12012000
12.4	144.1	3.0	21.1	1.37.00	12012000
13.2	147.8	3.0	20.4	1.47.00	12012000
13.3	150.3	3.0	20.4	015700	12012000
12.8	148.3	2.5	21.1	020700	12012000



WindSpeed	Dir	Usdv	Gust	Time	Date
14.3	137.6	2.9	22.7	0:7	00/12/01
14.3	144.6	2.8	21.9	0:17:00	00/12/1
13.9	146.5	2.9	21.1	0:27:00	0/12/1



[4] Intentionally (for better understanding), the first lines of the date and time columns contain various format types.

```
     14.1          144.0       2.9    22.7     00:37:00 2000-12-1
     13.4          146.6       2.7    21.1     00:47:0  2000.12.1
     13.1          144.3       2.6    20.4     0057     00.12.1
     12.4          142.1       2.8    20.4     0107     2000-12-01
     12.6          140.6       2.5    19.6     0117     2000/12/01
     12.8          146.5       3.2    21.9     1.27.00  20001201
     12.4          144.1       3.0    21.1     1.37.00  20001201
     13.2          147.8       3.0    20.4     1.47.00  20001201
     13.3          150.3       3.0    20.4     015700   20001201
     12.8          148.3       2.5    21.1     020700   20001201
```

```
Site Name:     SOMEWHERE
Site Number:    1

Start Time:     18:57   03/01/2000
Finish Time:    15:00   03/27/2000
Total Time:     25  day(s)  20  hour(s)  3  minute(s)

   DATE      TIME  Anem A   Anem A      Anem A           Anem A        Vane A
                   Other An Other An    Other An         Other An      Wind Van
                   Average  Avg Dev     Minimum          Maximum       Average
                   10 minut 10 minut    10 minut         10 minut      10 minut
                     m/s      m/s     m/s    dir   time m/s    dir   time   °
----------- ----- -------- -------- ---------------- ---------------- --------
Mar   1,2000 18:57    10.1       1.2     7.9 236 18:59   11.6 211 18:59    222.2
Mar   1,2000 19:00    11.5       0.8     9.4 221 19:05   13.2 219 19:04    222.2
Mar   1,2000 19:10    12.2       0.7    10.6 226 19:17   13.4 224 19:19    222.2
Mar   1,2000 19:20    12.1       0.7    10.0 225 19:22   13.1 228 19:25    226.4
Mar   1,2000 19:30    11.2       0.7     9.6 228 19:31   12.4 219 19:30    227.8
Mar   1,2000 19:40    10.9       0.6     9.1 225 19:44   12.0 233 19:49    226.4
Mar   1,2000 19:50    10.8       0.8     9.1 243 19:54   12.7 245 19:59    236.2
Mar   1,2000 20:00    10.4       1.0     8.4 277 20:04   13.0 250 20:06    250.3
Mar   1,2000 20:10    11.4       1.2     8.2 246 20:15   15.8 245 20:18    253.1
Mar   1,2000 20:20    12.3       1.2     9.8 250 20:21   14.3 246 20:25    251.7
```

Wind Speed (m/s)	Wind Direction (°)	Wind Speed SDV	Temperature (°C)	Solar Radiation (W/m2)	Gust of Wind Speed [m/s]	Time	Date	Lines to skip
3	11	4			8	2	1n	13

<u>Multiple anemometers - vanes</u> *(within the same mast)*

When multiple anemometers and wind vanes are present, *WindRose* provides some additional results (i.e.: wind shear, Weibull distributions per height, etc). In that case, the column numbers of each device, should be separated by a semicolon `;`. Furthermore, the heights of the anemometers should be set accordingly (in ascending order) in the 2^{nd} table of the `Input` sheet.

File Names	Column Numbers								
	Wind Speed (m/s)	Wind Direction (°)	Wind Speed SDV	Temperature (°C)	Solar Radiation (W/m2)	Gust of Wind Speed [m	Time	Date	Lines to skip
c:\data\site1\st010604.000	21;17;13;9;5	33;29;25	22;18;14;10;6	37		20;16;12;8;4	2	1	33

Multiple anemometers and vanes: Example form of `Input` *sheet's 1st table.*
Case with 5 anemometers and 3 wind vanes.

Measurements Height :	
above Ground level (m)	**10;20;30;40;50**

Setting the corresponding anemometers heights (`Input` sheet's 2nd table). In this example the 21st column contains the wind speed at 10m height.

The **second table** of the `Input` sheet contains all the necessary parameters characterising the analysis to be performed. These parameters are:

- The measuring period (start and end dates)
- The time interval of the measurements (10 minutes, 1 hour, etc)
- The limit for the calm, which is the value of the wind speed below which the response of the wind direction measuring device is not reliable (recommended value: 2m/s)
- The number of the direction sectors (16, 12 or 8) that the program will use (recommended value: 16)

Title1	**(Site's name)**
Title2	**(comment)**
Start from	**18/12/1999**
End at	**29/5/2000**
Minutes between data	**10**
Limit for calms (m/s)	**2**
Number of Direction Sectors	16 ▼
Measurements Height :	
above Ground level (m)	**10**
above Sea level (m)	**300**
Calcul. of mean turbulence	
at wind speed (m/s)	**10**
± bin width (m/s)	**1**
Wind Turbine selected	NEG Micon 750/48 ▼
Exponent coefficient (α)	**0.08**
Weibull method	"paper" method ▼
low limit (m/s)	**4**
high limit (m/s)	**16**
Wind Speed Uncertainty	
Calibr. error at Umean (m/s)	**0.06**
Anemometer's max speed m/s	**40**
Data Logger's precision (bits)	**8**
Site Correlation	
file name	
Export processed data	
file name	

The necessary parameters for the wind data analysis (sheet `Input`)

- The wind turbine for which energy calculations will take place.
- The exponent coefficient of the Power Law, which is used to extrapolate the Mast's wind speed at the Hub height of the wind turbine. This coefficient is used **only** when one anemometer is present on the Mast. If two or more anemometers are present, then this coefficient is calculated analytically (per wind speed bin and direction sector, more details in § *SHEAR*). **The given value refers to 5m/s**. Since it is not realistic to consider a constant value for the entire wind speed range, a simple model is used to "expand" it: every 5m/s this value is divided by two. Thus, if 0.08 is set, then at 10m/s is 0.04, at 15m/s is 0.02, etc. A linear regression is used for the intermediate values and the double of it is considered at 0m/s (0.16 in the above example).
- The Weibull distribution calculation method. In brief, 2 methods are proposed for the calculation of the *(k, C)* coefficients: a) using only the mean and the standard deviation of the wind speed and b) using the data distribution, restricted or not to a specific range (i.e.: 4-16m/s).[5] The second method is recommended. More details can be found in the Appendix § *WEIBULL DISTRIBUTION*.
- The wind speed uncertainty in case of analogue anemometers (i.e.: the output signal of the anemometer is analogue voltage). These parameters are not used in case of anemometers producing pulses/revolution.[6]
- The name of the (intermediate) file that must be created when site correlation will take place (details in the *CORRELATIONS* chapter).
- The name of an ASCII file into which all the row data are exported. This is particularly useful when delivering long term data (i.e.: yearly) that are stored originally in many files and/or to which correction coefficients were applied[7].

[5] The 2 values below the selected Weibull calculation method are taken into account only if the 2nd method is selected.

[6] Uncertainty calculation for "pulsed-ouput" anemometers will be added in the next program release.

[7] The created export file includes all the corrections, so no corrections should be applied if it is further processed.

Correction Coefficients									
Wind Speed MULT	Wind Speed OFFESET (m/s)	Wind Direction MULT	Wind Direction OFFSET (°)	Temperature MULT	Temprature OFFSET (°C)	Solar Radiation MULT	Solar Radiation OFFSET (W/m	Time MULT	Time OFFSET (sec)
			-38						
									600

A sample of the correction coefficients table (sheet `Input`*).*

The **third table** of the `Input` sheet includes correction coefficients per each file. The correction applied has the form: $\alpha{\cdot}x+\beta$ and is intended for the processing of measured quantities, when:

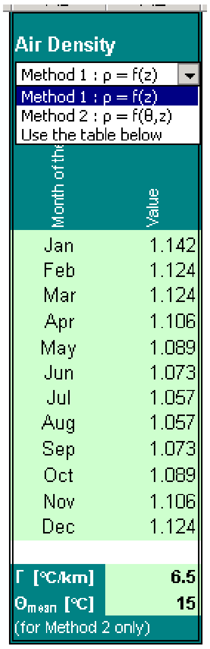
1. A systematic error occurred during the measurements campaign (i.e. wrong calibration factors, additional offset for the "zero" of the wind vane, etc)
2. Recorded data have different units (temperature in Fahrenheit degrees, wind speed in miles/h, wind direction in radians, etc…)

If no values are given, then the multipliers α and the offsets β are set to 1.0 and 0.0 respectively.

The following important issues have to be pointed out when applying correction coefficients:

- If the wind speed has to be adjusted by means of the correction coefficients ($y=\alpha{\cdot}x+\beta$), then its standard deviation is automatically multiplied by the coefficient (α).
- When adjusting wind directions, if the resultant direction angle falls out of the [0°, 360°] interval then, is automatically adjusted.
- Applying correction coefficients on the time/date should be done with caution. Although, there is no problem using the offset β (in seconds), in order to simulate a wrong day or time setting, the multiplier α (if $\neq$ 1.0), can seriously affect the reliability of the measurements, as it modifies the sampling rate (time step) of the measurement campaign.

The **fourth table** of the `Input` sheet deals with the calculation method of the air-density, which seriously affects the wind energy calculations. If data contain time-series of **atmospheric pressure** and **temperature**, then this table **is <u>not</u> used**, since the air density is calculated from real data complying with IEC-61400-12. In the opposite case, three are the possible choices:



Selection of the method for the Air Density correction.

- The *"first method"* uses an empirical formula relating air-density only to the anemometer elevation (site height + anemometer height).
- The *"second method"* calculates air-density using both the height and the temperature. Two additional values are required: the vertical temperature gradient Γ (recommended value: 6.5ºC/km) and the estimated mean ground temperature (for the measurements period). If temperature data exist into the data files, then the recorded mean value is used instead.
- The *"third method"* uses 12 preset values, one per each month of the year. These values can be retrieved either from a nearby meteorological station or set intuitively.

The mean value of the air density used during the calculations is given in the `Results` sheet. More details on the air-density calculation methods and on the power curve corrections are given in the Appendix.

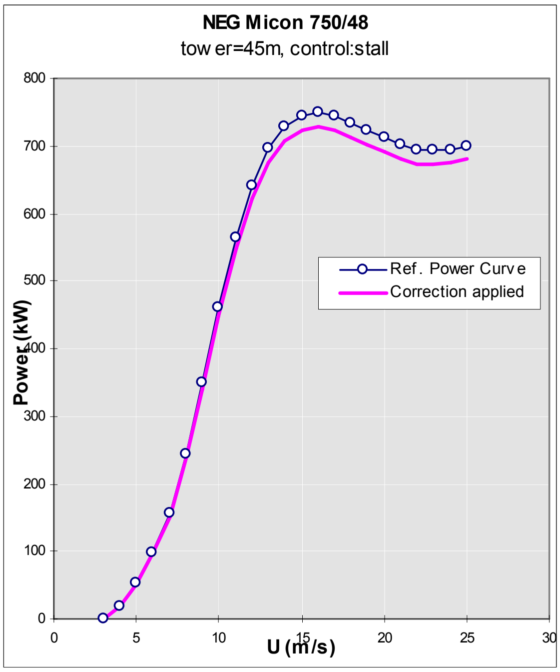
Power Curve

Pairs of columns, containing power curves of various wind turbines, compose this worksheet. Some representative power curves are included by default, but the user can add more or delete the existing ones. One restriction applies here: The user has to respect the form of the existing power curves (i.e. put in the Row1 cell the model name of the wind turbine, in the Row2 cell of the next column the tower height, choose the power control strategy, etc.).

Note

- A linear interpolation is performed in order to calculate the exact electrical power of the wind turbine, between the given values of the power curve.
- Whenever the measured wind speed is lower than the minimum value or greater than the maximum value of the power curve's wind speed then, the power is considered as zero and the wind turbine as out of operation.

NEG Micon 750/48	
tower (m):	45
diameter(m):	48
control:	stall
U (m/s)	Power (kW)
3	0
4	19.5
5	53.1
6	97.4
7	155.3
8	244.6
9	349.2
10	462.2
11	564.5
12	640.5
13	696.3
14	729.8
15	745.5
16	750
17	744.6
18	734.8
19	723
20	711.9
21	701.4
22	694.3
23	692.8
24	695.2
25	700.6



Left: *A sample of a power curve table (sheet* `PowerCurve`*).*
Right: *Its graphical representation including the correction due to the site elevation height (sheet* `Input`*)*

QUICK-CHECK OF THE DATA

Once the input sheets are filled correctly, the user can launch the *WindRose* by selecting *Run in English* or *Run in Greek* depending on the language in which the results will be displayed. Execution time depends on the amount of data; normally a Pentium-4 PC will take ½ minute to run 1-year data. When the execution is finished the figure below will appear displaying <u>all</u> the processed valid data. This is an important feature of the program, since Excel graphs cannot contain unlimited amount of data and the user interaction (zooming, scrolling) is limited.

Detailed view of <u>all</u> the processed data. Note that:
a) zoom operation is possible by selecting a region with the mouse
b) scrolling (panning) is achieved by holding the mouse down and dragging it to the desired direction.

An experienced user will find this screen particularly useful, as he can quickly deduce the quality of the data (spikes, fault operation of a device, etc.).

Displaying a smaller data "window" is also possible when the *View Mode* is set to: *Zoom X & Y* (or *Zoom X* if zooming is done only in the time axis). When a smaller data "window" is displayed, the user can smoothly move forward or backward, by selecting *Pan X & Y* (or *Pan X* just for the time-axis) and holding down the mouse while dragging it to the desired direction.

THE OUTPUT WORKSHEETS

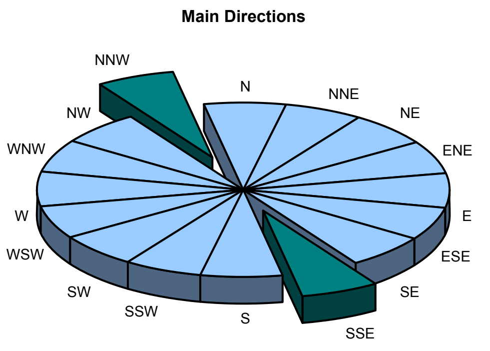
Results

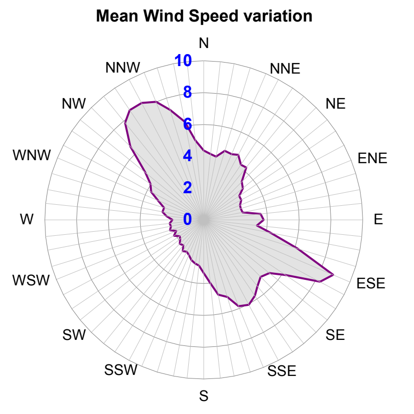
This one page sheet presents the summary of the performed analysis. The displayed quantities are:

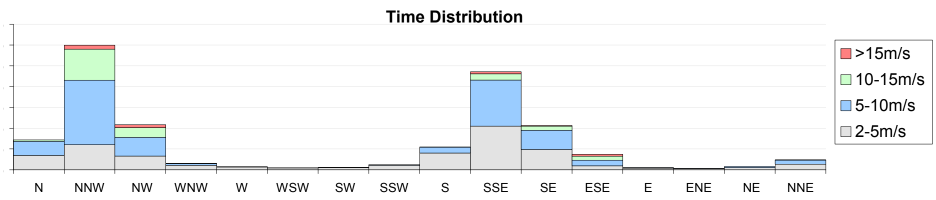
Measurements Period : from 4/2/2002 to 3/2/2003

Mean Annual Wind Speed (at 40m height)	6.2 m/s	(general mean= 6.0 m/s)
Mean Turbulence Intensity (at 10m/s)	9.2 %	
Max. 10min Average Wind Speed	27.2 m/s	(6/1/2003 07:50)
Maximum Gust	34.1 m/s	(6/1/2003 07:40)
Uncertainty of Wind Speed measurement	0.2 m/s	
Mean Wind Power	307.8 Watt/m²	
Total Wind Energy	2477.1 kWh/m²	
Weibull Distribution constants		
shape factor (k)	1.62	
scale factor (C)	6.7 m/s	
Total number of valid data	48280	
Included number of calms (<2m/s)	5593	
Missing data	4280 (8.1%)	
Expected W.T. energy production	3 740 376.3 kWh	(Gamesa G80-2.0MW
W.T. Capacity Factor	23.2 %	(ρ_{ave}=1.148kg/m^3)
Calc. Annual Mean Wind Speed at 67m height	6.6 m/s	(general mean= 6.5 m/s)
WT Annual Energy Production & cap. factor		
calculated from data distribution	4 157 412.3 kWh	23.71 %
calculated from Weibull distribution	4 121 376.8 kWh	23.51 %

Best Sector in Energy contain	NNW	41.22 %
2nd best Sector in Energy contain	SSE	20.64 %
Best Sector in Time distribution	NNW	29.95 %
2nd best Sector in Time distribution	SSE	23.59 %







The main results of the WindRose program (worksheet: `Results`*).*

- The mean wind speed. Note that, if more than 1-year data exist then, apart from the mean value of all the wind speed data, the *"annual mean"* is also provided. The calculation method of this value (see § below) assures that non-stationary effects, such as seasonality, are not taken into account.
- The turbulence intensity (at the specified wind speed range).
- The maximum wind speed and the date of its occurrence
- The maximum gust (1sec value) and the date of its occurrence (if a gust column was set in the `Input` sheet).
- The mean power of the wind per area (in units of kW/m^2).
- The total wind energy per area ($kWh/\ m^2$).
- The coefficients of the Weibull distribution that fits all the data.
- The total number of valid data within the specified time period (by the Start-Stop dates given at the `Input` sheet)
- The percentage of the missing data.
- The number of calms (wind speed below a threshold)
- The expected electrical energy production (kWh) of the selected wind turbine during the given period of measurements, for all the valid data.
- The capacity factor of the wind turbine (percentage of the nominal power of the wind turbine, at which the machine should operate continuously to produce the expected electrical energy)
- The estimated mean wind speed at the nacelle height of the wind turbine. Similarly with the measured mean wind speed, if more than 1-year data exist, then the given value is the average of 12 monthly values. Each monthly average value is weighted with the completeness of the given month for all the years.
- The expected Annual Energy Production (AEP) in kWh and the corresponding capacity factor. Both are calculated by two methods: a) from the data distribution and b) from the Weibull distribution. If 12-month data exist, then the AEP is calculated from the 12 distributions. In the opposite case (less than 1-year data), the AEP is calculated from the general average distribution.
- The two best direction sectors in wind energy contain.
- The two best direction sectors in terms of time.

Note that, the "*annual mean*" wind speed calculation takes into account the various data completeness of each month, during all the years of measurements. Averaging the 12 months, assures that the result a) represents the 1-year reference period and b) is not biased by data that fail to cover exactly 12, 24, 36, etc months. Below, an arithmetic example is given, representing the described procedure.

```
STEP 1                              | STEP 2
                                    |
 Month      Mean       Data         | Month    Mean       Data
            Wind Speed  Complet.    |          Wind Speed Completeness
---------  --------  ----------     |  -----   ----------------------
Jan. 2003     9.3      100 %        |  Jan.    9.86(*)    77 %
Feb. 2003     7.0      100 %        |  Feb.    7.64       99 %
Mar. 2003     6.9      100 %        |  Mar.    6.6       100 %
Apr. 2003     6.3       60 %        |  Apr.    7.36       80 %
May  2003     5.3      100 %        |  May     6.3       100 %
Jun .2003     6.9      100 %        |  Jun.    6.45       91 %
Jul. 2003     7.7       99 %        |  Jul.    7.7        99 %
Aug. 2003     8.5       90 %        |  Aug.    8.5       100 %
Sep. 2003     6.0      100 %        |  Sep.    6.0       100 %
Oct. 2003     6.4      100 %        |  Oct.    6.4       100 %
Nov. 2003     8.1      100 %        |  Nov.    8.1       100 %
Dec. 2003     7.9       75 %        |  Dec.    7.9        75 %
Jan. 2004    10.9       54 %        |
Feb. 2004     8.3       98 %        |  STEP 3
Mar. 2004     6.3      100 %        |---------------------------------------
Apr. 2004     8.0      100 %        |  Mean Annual Wind Speed = 7.4
May  2004     7.3      100 %        |  = ( 9.86+7.64+6.6+7.36+6.3+6.45+
Jun. 2004     5.9       82 %        |     +7.7 +8.5 +6.0+6.4 +8.1+7.9 )/12

                                        (*)9.86 = (9.3*1.0+10.9*0.54)/1.54
```

Why 3 values for the expected W.T. Energy production?

- The 1st value refers to the energy production of the wind turbine for the <u>given time period</u>, while the other 2 refer to the <u>annual</u> production.

- The 1st value <u>depends on the missing data</u>, as it is calculated only by the valid data, within the given time-period. The other 2 values are the outcome of the projection of the 2 distributions (data and Weibull) to 1-year. Thus, the notion of missing data is not applicable to them.

- If the given time-period (defined by the *Start*, *Stop* dates) is one year then, the 3 values should converge. In fact, if there is no missing data then, the 1st and the 2nd values should be practically the same. If the 3rd value is close enough to the other two, it means that the given Weibull distribution coefficients *(k, C)* fit well the data and can be used safely to characterize the site.

- For the same reasons there are also 3 wind turbine capacitor factors.

How the W.T. Energy production is calculated?

- The wind turbine energy production is based on the wind speed estimation at hub height. If measurements are not taken at the WT's hub height, then the wind speed is extrapolated to that height. For that, the "power law" is used in order to calculate the wind shear.

- When the wind speed is measured at different heights, then the detailed wind shear (per direction and per wind speed) is calculated. If the wind speed is measured at only one height, then a uniform shear is assumed, based on the exponent coefficient $\boldsymbol{\alpha}$ of the power law.

- Having calculated the wind speed time-series at hub height, the energy production is evaluated using the "corrected" power curve.

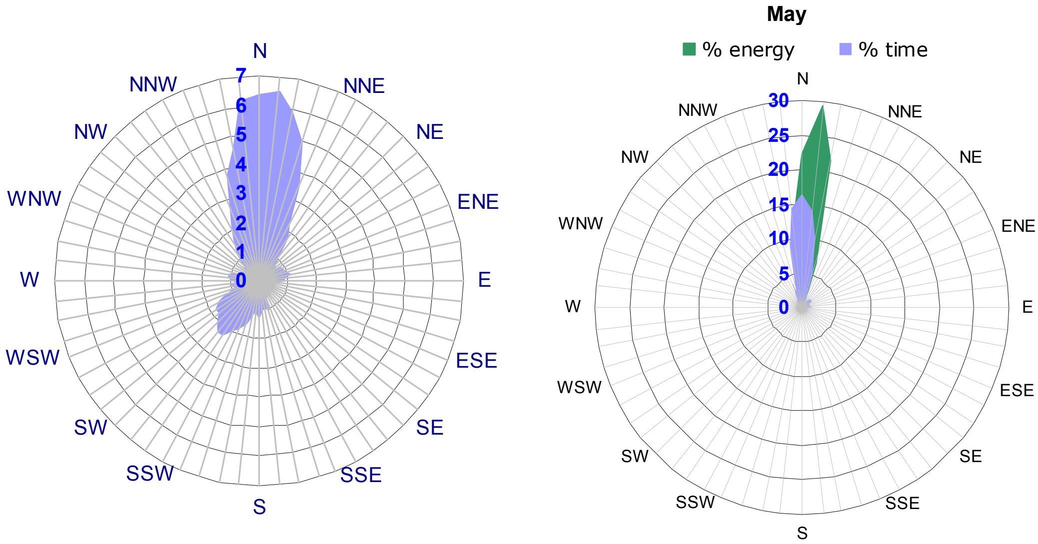
- Usually, the power curves given by the WT manufacturers refer to the sea level, where $\rho=1.225 kg/m^3$. Therefore, the air density at the specific site elevation needs to be evaluated (using 3 different methods, including or not temperature time-series, etc). Finally, this *local* air density and the type of the power control of the wind turbine (i.e.: stall or pitch), provide the "corrected" power curve, according to the IEC-61400-12 recommendation.

Two charts are shown below the results table: A pie chart presenting schematically the most prevailed directions of the site and a polar chart showing the variation of the mean wind speed as a function of the direction.

Finally, the data distribution in time per direction sector is given. Each bar is composed by 4 parts, depending on the percentage of time that the wind speed at the specific sector falls in the 4 preset ranges[8]: [2m/s-5m/s), [5-10m/s), [10-15m/s), [>15m/s).

WindRose

This sheet is composed by the total and the monthly wind roses (distribution chart in polar co-ordinates). They present the wind speed distribution (%) per direction, in the time and energy domain.



Samples of a site's wind roses (total and monthly)

Note that, for maximum precision, the polar plots are divided in 64 sectors, each 5.625° (=360°/64) wide. Each point of the drawn line, represents the mean value of all the data within this sector, i.e. the value of the distribution at 0° is the mean value of all the data found within the sector [-2.8125, +2.8125).

It is reminded here that, in order to calculate both time and energy distributions per direction sector, only data with wind speeds greater than the calm limit (set in the `Input` worksheet) are taken into account. If the user wants to change this and take into account the total data, he has to set the calm limit to 0m/s and re-run the program.

Finally, note that the energy refers to the energy of the wind, not the estimated electrical energy of the wind turbine. Although, in most of the cases the two distributions are identical, differences might exist in case of very high wind speeds (greater than the cut-out wind speed), where the wind turbine is supposed to shut down.

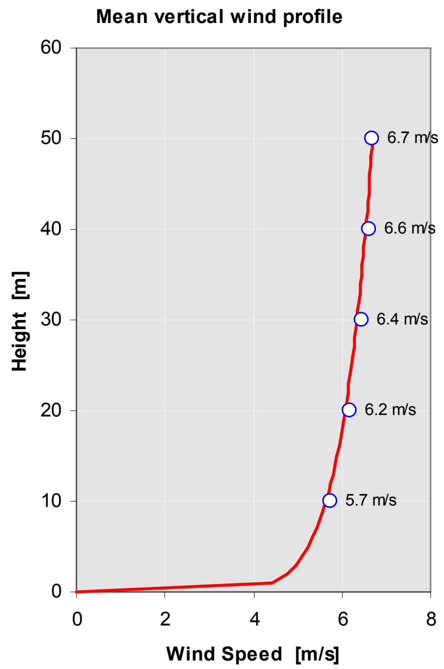
[8] The low limit is actually the calm threshold value (as set in the `Input` sheet), below of which the response of the wind direction measuring device is not reliable.

Shear

This Excel worksheet is created automatically only if multiple anemometers are present. The first graph shows the mean wind speed values (as measured) along with the average vertical wind shear. Wind shear calculations are based on the "power law":

$$u(z) = u(z_{ref}) \left(\frac{z}{z_{ref}} \right)^{\alpha}$$

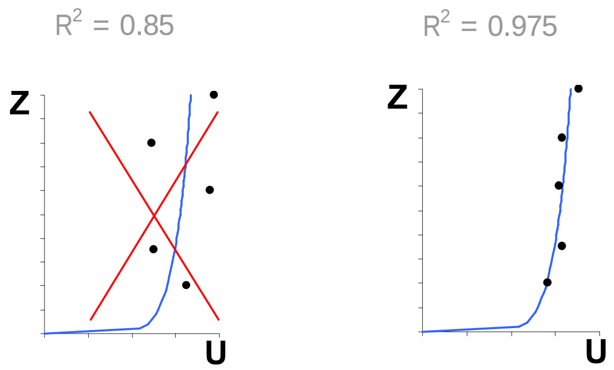
where the z_{ref} denotes the height at which the wind speed u(z_{ref}) is measured and α is the wind shear exponent coefficient.



Mean wind speed per height – measurements & mean vertical shear (sheet `Shear`*)*

The next table shows the measured mean and max wind speeds per direction and per height. At the end, the calculated values are given for the hub height of the selected wind turbine. The variation of the Weibull coefficients per height and per direction is given in another separate table. Both tables provide results at hub height, based on the extrapolated wind speed time-series at that height (from the higher anemometer) using the wind shear results.

The last table of this worksheet presents in detail the average value of the exponent coefficient α of the "power law" per wind speed and per direction. For each time step one value of α is calculated. Values of α are considered valid, only if the goodness of fit R^2> 0.95. Note that, a) this value is user selectable from *"Advanced Options…"* of the *WindRose* menu and b) it is displayed on the top of that table, along with the data percentage satisfying that condition, providing thus an indication of the validity of the Power Law at the specific site.



Measured wind speed (black dots) and calculated wind shear: Goodness of fit criterion: Left: $R^2<0.95$ rejected. Right: $R^2>0.95$ accepted

Average and Max (10min) wind speed per direction

Height	U	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW	N	All Dirs	
10	Ave	6.84	5.59	3.62	3.19	4.37	5.35	5.04	5.07	4.76	3.88	6.06	6.98	**5.75**	(measured)
	Max	16.85	13.52	8.18	8.79	16.57	13.06	12.34	11.84	10.91	10.88	16.03	19.03	19.03	
20	Ave	7.29	6.07	3.78	3.35	4.57	5.61	5.39	5.66	5.57	4.27	6.42	7.32	**6.17**	
	Max	17.58	14.48	8.86	9.17	16.75	13.15	13.11	13.68	13.39	13.27	16.55	19.50	19.50	
30	Ave	7.72	6.52	4.07	3.24	4.64	5.70	5.77	6.10	6.04	4.49	6.51	7.45	**6.44**	
	Max	18.03	15.50	9.73	9.20	16.65	13.52	13.85	14.83	15.06	14.37	16.46	19.60	19.60	
40	Ave	7.98	6.65	3.86	3.47	4.63	5.70	6.00	6.37	6.29	4.62	6.65	7.64	**6.62**	
	Max	18.27	15.78	9.80	9.52	16.30	13.84	14.56	15.15	15.54	14.43	16.67	19.85	19.85	
50	Ave	8.00	6.65	4.39	3.50	4.59	5.67	6.07	6.51	6.46	4.72	6.74	7.67	**6.69**	
	Max	18.37	15.82	9.84	9.42	16.18	13.92	14.88	15.55	16.02	14.83	16.94	20.04	20.04	
80	Ave	8.41	7.03	4.60	3.60	4.66	5.77	6.45	7.03	7.08	5.01	6.96	7.90	**7.02**	(calculated)
	Max	18.85	16.62	10.41	9.60	16.06	14.24	15.87	16.86	18.04	16.25	17.25	20.33	20.33	

Mean wind speed per height and per direction (sheet `Shear`*)*

Weibull parameters per Height

Height	Const	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW	N	All Dirs
10	k	2.60	2.80	2.76	1.84	1.54	2.45	2.24	2.46	2.63	2.25	1.92	2.33	**2.01**
	C	7.8	6.3	4.2	3.3	4.7	6.1	5.7	5.7	5.3	4.2	6.7	7.9	**6.4**
20	k	2.65	2.72	2.46	1.97	1.57	2.45	2.24	2.49	2.48	2.04	1.79	2.35	**2.08**
	C	8.2	6.8	4.3	3.6	4.9	6.4	6.1	6.3	6.3	4.5	7.1	8.2	**6.9**
30	k	2.64	2.67	2.48	1.94	1.66	2.46	2.11	2.47	2.49	2.01	1.78	2.34	**2.10**
	C	8.7	7.3	4.7	3.5	5.0	6.5	6.6	6.8	6.8	4.8	7.2	8.4	**7.2**
40	k	2.62	2.63	2.24	1.92	1.66	2.49	2.07	2.49	2.49	2.08	1.78	2.35	**2.08**
	C	9.0	7.4	4.4	3.7	5.0	6.5	6.8	7.1	7.1	5.0	7.4	8.6	**7.4**
50	k	2.59	2.62	2.63	1.96	1.66	2.48	2.05	2.45	2.51	2.10	1.76	2.33	**2.09**
	C	9.0	7.4	5.1	3.8	5.0	6.4	6.9	7.2	7.3	5.2	7.5	8.7	**7.5**
80	k	2.55	2.53	2.64	2.01	1.70	2.46	1.94	2.41	2.40	2.02	1.71	2.31	**2.07**
	C	9.5	7.8	5.3	3.9	5.1	6.5	7.3	7.7	8.0	5.5	7.7	8.9	**7.9**

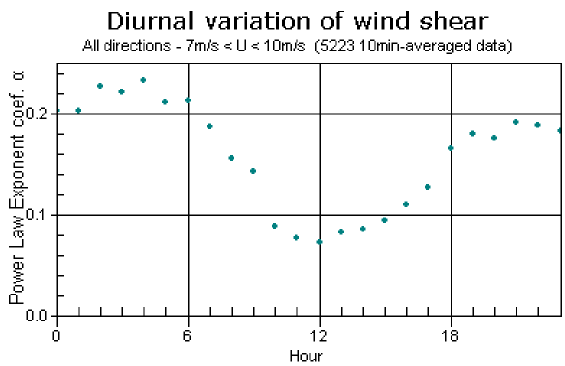
Variation of the Weibull distribution parameters, per height and per direction (sheet `Shear`*)*

Wind Shear exp. coef. α Data percentage with R^2>0.95 : 90.25%

m/s	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW	N	average
5-6	0.045	0.138	0.207	0.365	0.159	0.175	0.218	0.242	0.310	0.165	0.166	0.080	0.165
6-7	0.079	0.100	0.223	0.388	0.130	0.144	0.160	0.188	0.357	0.278	0.164	0.099	0.146
7-8	0.049	0.179	0.249	0.401	0.161	0.099	0.090	0.162	0.374	0.398	0.175	0.099	0.124
8-9	0.068			0.369	0.186	0.113	0.100	0.118	0.355	0.424	0.152	0.086	0.119
9-10	0.090				0.167	0.095	0.097	0.176	0.396	0.525	0.172	0.077	0.107
10-11	0.104			0.411	0.180	0.120	0.113	0.168	0.404		0.134	0.075	0.101
11-12	0.093			0.351	0.211	0.108	0.110	0.147	0.475	0.482	0.102	0.079	0.106
12-13	0.103			0.344	0.250	0.129	0.081	0.166	0.474	0.465	0.083	0.079	0.107
13-14	0.100			0.344		0.124	0.109	0.178	0.363		0.050	0.073	0.091
14-15	0.109			0.369		0.129	0.119	0.156	0.404		0.092	0.075	0.095
15-16	0.110					0.120	0.090					0.078	0.087
16-17	0.097					0.122	0.088				0.126	0.078	0.084
17-18	0.099				0.185	0.144	0.035				0.066	0.078	0.082
18-19	0.081					0.186	0.093					0.076	0.080
19-20							0.074					0.070	0.070
20-21						0.221	0.104					0.070	0.075
21-22							0.017					0.070	0.069
22-23												0.059	0.059
23-24												0.058	0.058
24-25												0.086	0.086
25-												0.062	0.062
average	0.088	0.139	0.227	0.371	0.181	0.135	0.100	0.170	0.391	0.391	0.124	0.077	**0.116**

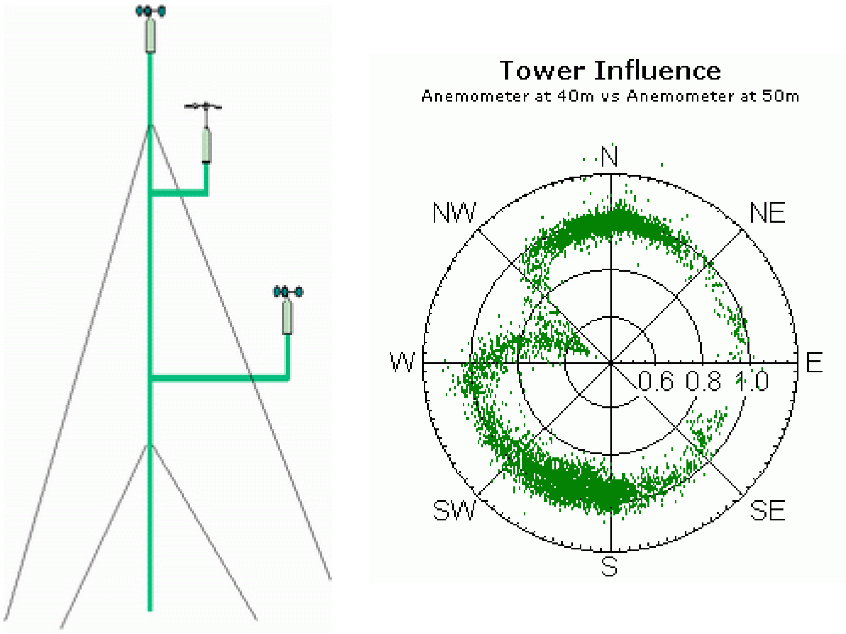
Wind shear exponent results per wind speed and direction. *(sheet `Shear`)*

Here it is underlined that, internally, the above table is calculated also for each month and for each hour of the day. The reason is the significant variability of the exp. coefficient *α* with these two parameters. Thus, when calculating the wind speed at a higher height (ie: hub height), if such values of *α* exist (per hour, per month, per wind speed and per direction), then they are preferably used, rather than the (summarized) ones of the above table.



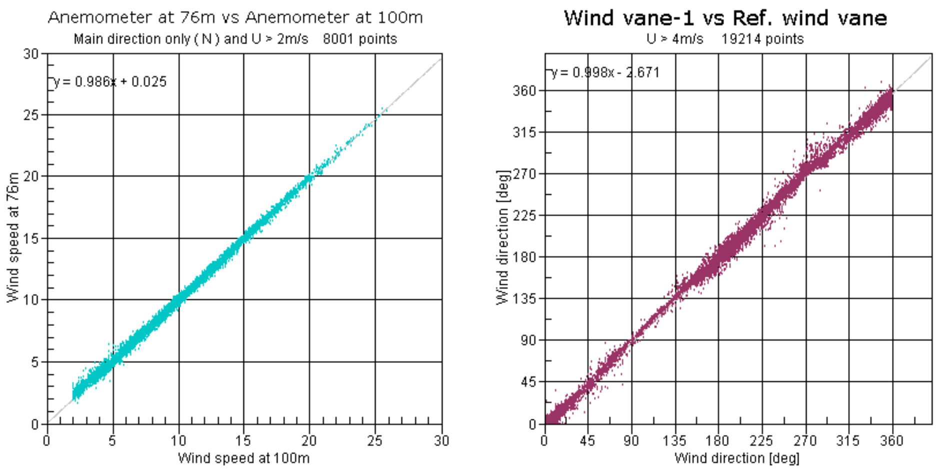
A typical graph showing the diurnal variation of the exponent coefficient a with the hour of the day. Result from Lavrio site (worksheet: `Shear`).

At the end of the *`Shear`* sheet, a series of polar graphs are created showing the influence of the mast tower "shadow" on the (lower) anemometers, assuming that the reference anemometer is installed on the top of the mast, where the wind flow is undisturbed, no matter the wind direction. This is achieved by plotting the wind speed ratios above a threshold (4m/s).



Influence of the mast tower "shadow" on the (lower) anemometers.
Polar plot of the wind speed ratio of a lower anemometer versus the top one (worksheet: `Shear`).

In the above example, note that at ~300° the anemometers ratio falls around 0.5, providing valuable information about a) the exact orientation of the boom and b) the boom length sufficiency according to the standards. A less pronounced drop of the ratio is also observed, as expected, diametrically at ~120°.



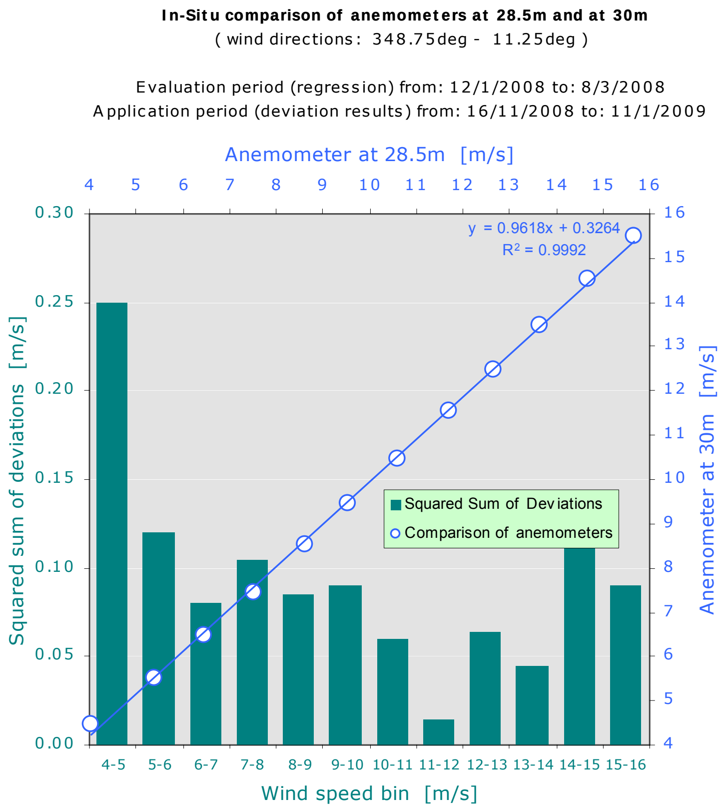
Comparison of anemometers and vanes mounted on the same Mast (worksheet: `Shear`).

These graphs are automatically created for all the low anemometers in respect to the reference one, without any user interaction. However, since Excel cannot handle more that 32000 data per graph, an external graph library is used to create them in a form of a PNG picture. Consequently, these graphs cannot further customized, as other Excel graphs in *WindRose.XLS*.

AnnexK

This Sheet is created only if multiple anemometers are present and sufficient data exist (ie: several months). Ideally, cup anemometers should be calibrated in a wind tunnel after the measurement period, in order to assure the accuracy of the measurements, during the entire measurement campaign. Another (inferior) possibility is to perform an *in-situ comparison* between the top and the control anemometer (usually 1.5m below the top one). This procedure is defined in the Annex K of the IEC-61400-12-1 standard.

Briefly, the procedure can be summarized as follows: Data are filtered for a narrow direction sector and classified in bins of 1m/s. Then, a linear regression is performed between the two anemometers, using data from the initial 1-2 months. Finally, the regression results are applied to the last 1-2 months of the measurements and compared to the real data.



The main result of the Annex K sheet

The main result of the *AnnexK* sheet is a (complex) graph with 4 axes. In the blue axes (*x*-top, *y*-right) the linear regression between the two anemometers is presented. In the green axes (*x*-bottom, *y*-left) the square sum of the systematic and statistical deviations per wind speed bin are plotted. The *in-situ comparison* is considered successful (and a recalibration of the anemometers is not necessary), if each bar remains lower than 0.1m/s. The examined condition can be written as follows:

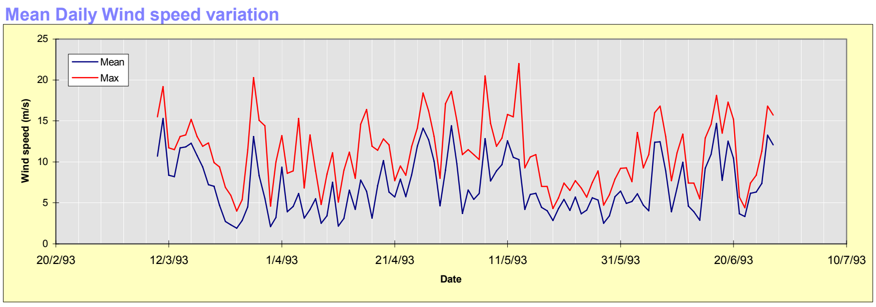
$$\sqrt{\overline{\Delta U}^2 + \left(\frac{\sigma_{\Delta U}}{\sqrt{N}}\right)^2} \leq 0.1 m/s$$

where: $\Delta U = U_{top} - (\alpha * U_{control} + \beta)$ with (α, β) being the regression coefficients for the initial period and N the number of data per each wind speed bin ($N \geq 3$ *10min data*).

The default and recommended parameters for this method are: i) select data from 6m/s to 12m/s ii) use intervals of 8 weeks for both the first and last part of the measurements and iii) apply the method to the main wind direction sector. However, these parameters can be modified within the "*Advanced Options…*" of the *WindRose* menu.

Time Charts

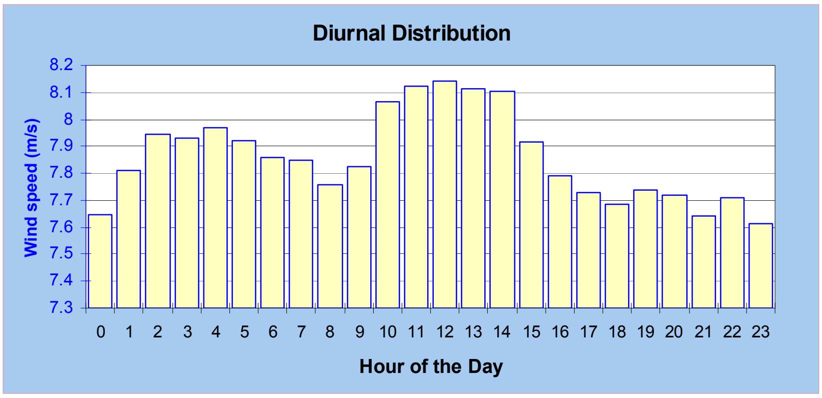
Three important figures are presented in this worksheet, displaying the results of the wind data analysis in a "global" form. More detailed "views" of the results are presented in the next worksheets.



Wind speed variation per day (mean & max. values)

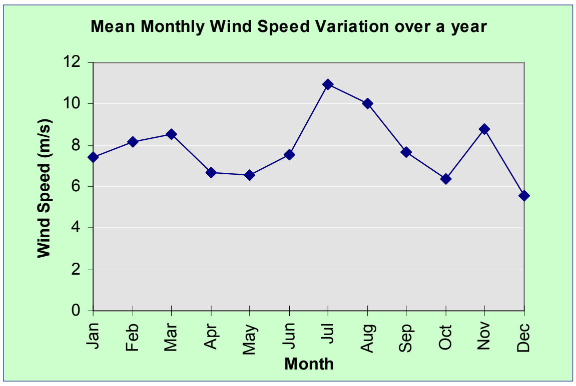
- The 1st one shows the evolution of the daily mean wind speed, as well as, the maximum wind speed occurred per day, for the given time-step (i.e. if 10minutes series are recorded, the maximum value is of course, not the instantaneous 1sec gust, but the maximum 10minutes wind speed occurred during this day).

- The 2nd figure presents the Diurnal distribution. Actually, this is the distribution of the wind speed as a function of the hour of the day. All the data are taken into account here, independently of the wind direction. The Diurnal distribution per month is presented in the `12diurnal` worksheet.



Distribution of the wind speed per hour of the day.

- Finally, the 3rd figure shows the mean wind speed per month. If more than a year period is examined, each monthly mean wind speed is calculated from all the corresponding months.



Mean wind speed variation per month.

Tables

Two very essential tables are presented in this worksheet. The 1st one shows the variation of the % turbulence intensity (σ_u/U*100) over the wind direction and the wind speed. The 2nd one shows the total data distribution over both wind speed and direction. The following points should be noted here:

The "binning" of the wind speed is done in 25 steps of 1m/s, starting from the [0m/s, 1m/s), with the 26th one gathering all data higher than 25m/s. The table of the turbulence intensities does not show the first five velocity bins (the Excel's *"Hide cells"* option is enabled), as no physical meaning can be extracted from turbulence intensities, when the mean wind speed approaches to zero. In that case, the ratio σ_u/U takes very high values, dominating the rest ones in the graphical representation of the table (see worksheet:`3D`).

Data distribution vs Wind Speed & Wind Direction

m/s	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	N	totals
0-1	32	61	50	78	124	100	92	154	110	104	141	189	229	166	38	36	1704
1-2	41	55	80	142	141	175	134	158	158	224	315	436	493	337	47	42	2978
2-3	31	49	69	187	239	255	140	141	139	304	483	782	784	428	64	22	4117
3-4	16	27	61	139	206	215	127	153	161	361	720	1338	797	288	18	7	4634
4-5	9	5	18	60	167	209	158	189	142	284	899	2165	862	106	10	7	5290
5-6	18	8	11	33	139	243	220	148	105	236	609	2351	782	65	22	13	5003
6-7	7	2	1	14	144	218	218	130	91	208	430	1988	1004	88	10	3	4556
7-8				15	115	265	204	54	91	177	246	1463	1131	106	5	1	3873
8-9	1			10	69	168	122	31	93	138	151	1272	1298	120		2	3475
9-10				7	46	184	78	28	52	135	122	995	1413	137	1		3198
10-11				5	31	218	77	26	42	83	76	1163	1439	176			3336
11-12				4	46	205	71	19	23	71	72	1159	1338	250	1		3259
12-13				10	23	211	81	26	26	61	30	1004	1245	177	1		2895
13-14				4	16	191	37	23	20	33	22	938	1238	57	2		2581
14-15				5	14	122	34	13	15	51	6	813	1100	44	1		2218
15-16				4	6	86	27	4	2	63	3	430	933	40	1		1599
16-17				8	6	93	26	6		22		162	684	58	2		1067
17-18				10	6	58	12	3		8		29	524	30			680
18-19				12	1	37	7	2		2		6	470	11			548
19-20				4		18	11	1				1	308	11			354
20-21				1	1	18	8						189	3			220
21-22						8	6						89				103
22-23						1	4						25				30
23-24							2						5				7
24-25							3						3				6
25-							1										1
totals	155	207	290	752	1540	3298	1900	1309	1270	2565	4325	18684	18383	2698	223	133	57732

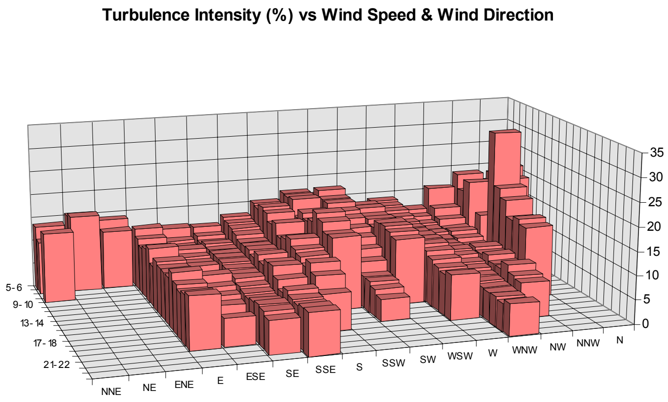
`Tables` *worksheet: Data distribution per wind speed and direction.*

The number of the wind direction sectors is the one selected in the Input worksheet (8, 12 or 16). As mentioned before, each direction refers to the mean angle of the corresponding sector. For example: suppose that 16 sectors are selected (the default and recommended value), then the width of each sector is 22.5° (=360°/16) and the North winds are all whose angle falls into the [348.75°, +11.25°) sector.

The mean turbulence intensity, per wind speed and direction bin, is calculated using the classical averaging methods; no correction takes place. Although not precise, this simple method provides a satisfactory approximation of the *"true"* turbulence intensity, which could be calculated, only if the detailed wind speed time-series were available.

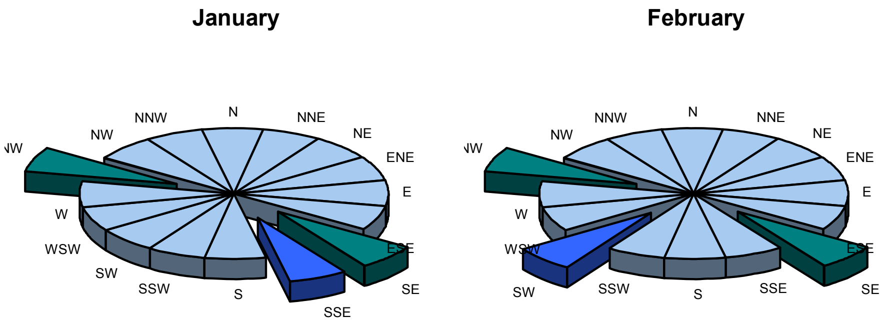
The number of successive rotations of the wind vane (clockwise and counter clockwise) is given in the 2^{nd} table. These revolution numbers, indicating the number of times that a wind turbine would have been rotated around itself, provide a good estimate of the number of times that the **electrical power cables are twisted**. For this calculation, all the data (including calms) have been taken into account, considering that even during low wind speeds, the wind turbine usually rotates for an optimum orientation. Obviously, the accuracy of the two numbers depends on the data completeness (low number of missing data).

3D This worksheet contains the 3D graphical representation of the `Tables` worksheet, showing the turbulence intensity distribution per wind speed and direction, as well as, the total data distribution again per wind speed and wind direction.



Turbulence intensity per wind speed and direction
(3D worksheet).

12pie In this 2-page worksheet 12 pie charts are plotted, one per month of the year, showing the two dominant wind directions. At the end of the 2nd page a table is also given with the numerical representation of the figures. In case that, a prevailed sector (referring to time) is not among the best two sectors (referring to energy) then a blue colour is used (or a green colour in the opposite case). As in the `WindRose` sheet, the calms are not included here too.

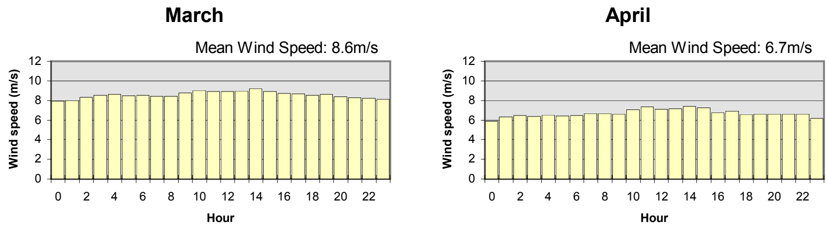


Main wind directions
*(**blue:** based on the time, **green:** based on the energy content).*

12diurnal This one-page sheet is composed by 12 bar-plots presenting the Diurnal distribution of the data, per month of the year (all years included). In fact, it is the hourly variation of the wind speed per month, all the directions taken into account. Note that, if the total diurnal distribution is needed, it can be found in the `TimeChart` sheet.

Important Note

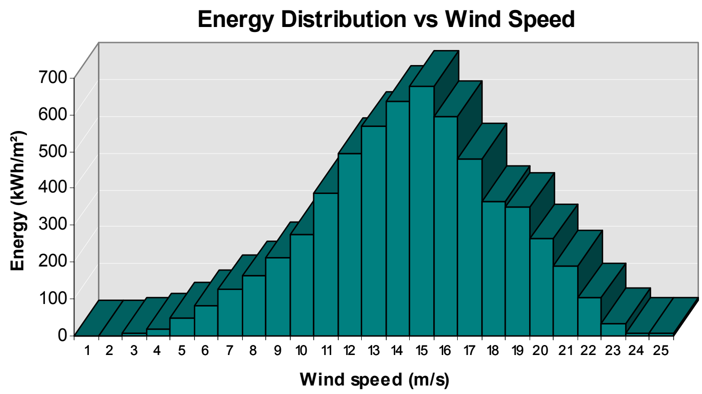
- If data exceed 1-year period the (monthly) graphs cumulate data from different years. When it is necessary to see the diurnal distribution of only one specific month, then the program should be run, once per year (specifying accordingly the start and end dates in the `Input` worksheet).



Example of the Diurnal distribution per month (`12diurnal` worksheet).

Bar Charts

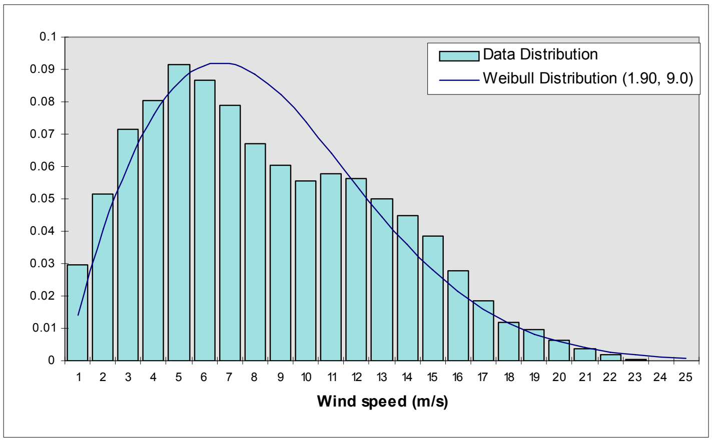
The 4 most common representations of the wind distribution are plotted in the present worksheet. The first two show the distribution of the wind, based on the energy (not the expected energy production of the wind turbine) as a function of the wind direction (1st one) and the wind speed (2nd one). The last two show the time-based distribution of the wind as a function of the wind direction (3rd one) and the wind speed (4th one).



Wind energy distribution versus wind speed.
(`BarCharts` worksheet).

Weibull

The main figure of this worksheet shows the Weibull distribution that fits the wind data. All the wind directions have taken into account when calculating the shape (*k*) and the scale (*C*) coefficients of the Weibull distribution in this graph. If multiple anemometers are present, the graph refers to the reference anemometer (usually the highest one).



Data distribution together with
the calculated Weibull distribution that fits the data.

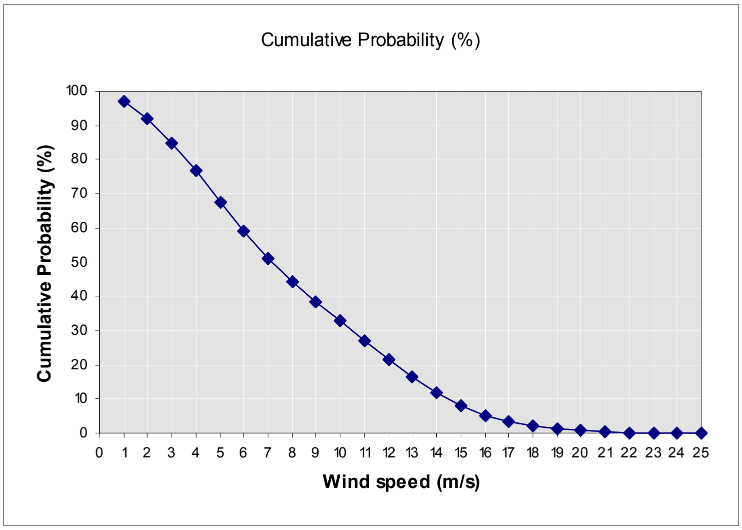
Some important information is included in the table below the graph. Here, the coefficients of the Weibull distribution are displayed per wind direction sector together with the corresponding percentage of the total data found in it, the mean wind speed, the turbulence intensity and the starting and ending values of the direction sector. Some third-party programs, dealing with optimum wind turbine arrangement within a wind farm (i.e.: WindFarm® by ReSoft), require as an input this table's data, as well as, the site's topography.

Direction	Angles (deg)	Weibull shape	Weibull scale	Data Distrib	Mean Wind Speed (m/s)	T.I. (%) at 10m/s
NNE	11.25 - 33.75	1.65	3.27	0.27%	2.5	
NE	33.75 - 56.25	1.79	2.73	0.36%	1.9	
ENE	56.25 - 78.75	1.65	2.97	0.50%	2.2	
E	78.75 - 101.25	1.42	5.69	1.30%	4.0	11.0
ESE	101.25 - 123.75	1.70	6.28	2.67%	5.0	9.5
SE	123.75 - 146.25	1.87	9.37	5.71%	8.3	9.3
SSE	146.25 - 168.75	1.72	8.40	3.29%	6.9	10.3
S	168.75 - 191.25	1.58	5.88	2.27%	4.7	14.2
SSW	191.25 - 213.75	1.71	6.11	2.20%	5.1	15.4
SW	213.75 - 236.25	1.85	7.23	4.44%	5.9	15.2
WSW	236.25 - 258.75	2.16	6.07	7.49%	4.9	14.0
W	258.75 - 281.25	2.36	8.98	32.36%	7.8	11.7
WNW	281.25 - 303.75	2.11	11.32	31.84%	10.2	8.8
NW	303.75 - 326.25	1.74	7.25	4.67%	6.7	8.6
NNW	326.25 - 348.75	1.53	4.37	0.39%	3.0	12.1
N	348.75 - 11.25	1.55	3.02	0.23%	2.3	

Weibull distribution coefficients, data percentage, mean wind speed and turbulence intensity, per direction sector.

In this version of *WindRose*, the calculated Weibull coefficients per month are given only as values at: `TempData!M109:O122` however, future versions will include a graphical representation.

The 2nd graph of the worksheet is the wind data accumulated probability (based on the data distribution, not on the Weibull distribution). It is a useful tool to estimate the percentage of the time that the wind speed exceeds a specific value, i.e. how much of the time the wind speed exceeds the cut-in or the cut-out speed of the wind turbine.

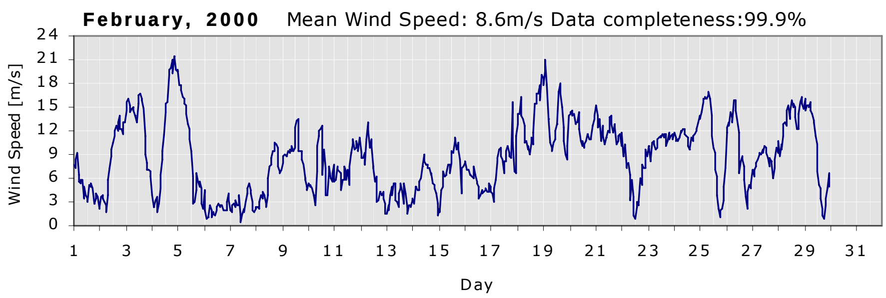


Cumulative data probability.
(i.e.: 33% of the time, the wind speed is higher than 10m/s).

The 3rd graph shows the variation of the turbulence intensity over the wind direction. The calculation is done using only wind speeds within the specified range in the `Input` worksheet (usually 10m/s ± 1m.s). Obviously, if a direction sector has no data in the specified wind speed bin, a zero is displayed. The discussion held in the description of the `Tables` worksheet about averaging turbulence intensities, applies here too. Safe conclusions can be obtained only when significant amount of data are found in each direction sector.

UhourT - UhourG

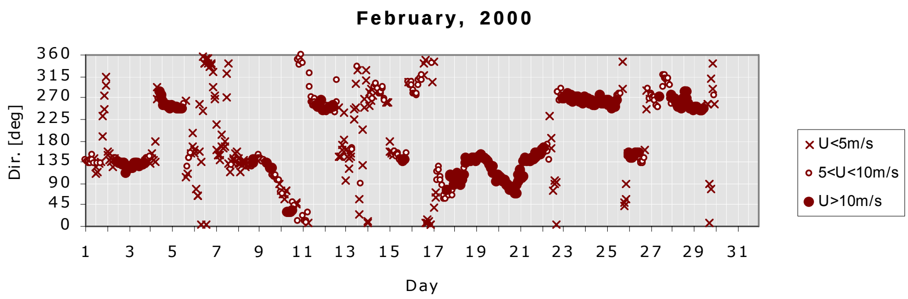
These 2 worksheets contain monthly tables (`UhourT`) and graphs (`UhourG`), representing the evolution of the mean hourly wind speed per day.



Variation of the mean wind speed per hour, during the month of January.
*(24 * 31=744 points plotted).*

DIRhourT - DIRhourG

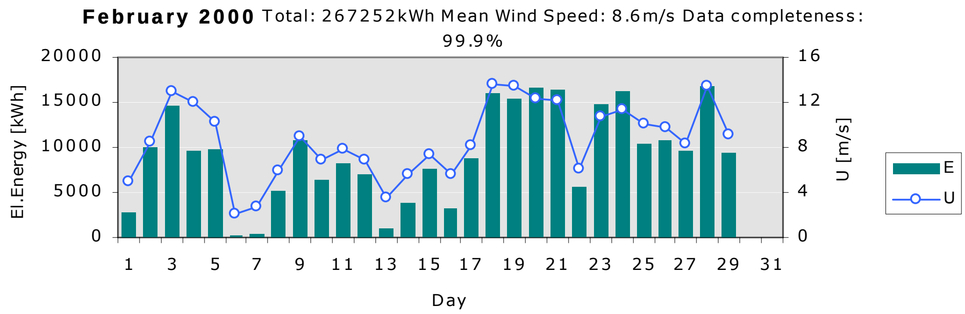
Similarly to the previous 2 worksheets, `DIRhourT` and `DIRhourG`, show the variation of the wind direction per day (mean value per hour), for each month.



Monthly Variation of the mean wind direction per hour

WTprodT - WTprodG

These 12 tables (`WTprodT`) and 12 graphs (`WTprodT`) represent the sum of the hourly wind turbine energy production per day, per month of the year. Note that the energy production results depend on the data completeness.

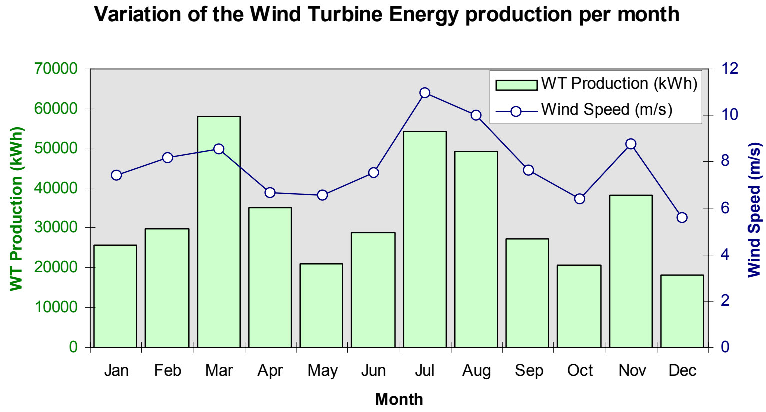


`WTprodG`: Variation of the WT's daily produced energy together with the mean wind speed.

February 2000 Total exp. production by Nordex N50/800: 267252kWh Mean Wind Speed: 8.6m/s

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Sum
1	313	276	410	504	188	132	95	133	151	25	107	58	21	18	87	75	99	63	8	5	20	38	24	3	2851
2	4	23	27	15	7	2	0	35	129	256	454	546	613	677	714	730	715	739	740	720	721	666	725	736	9992
3	735	718	711	727	739	735	731	739	739	740	738	723	701	697	709	713	730	673	473	351	242	241	228	151	14685
4	36	5	8	11	23	2	3	68	178	395	525	684	735	722	718	664	656	654	652	660	435	544	659	656	9698
5	658	678	680	689	707	709	723	727	743	724	721	651	506	172	16	6	58	193	106	83	113	70	8	2	9741
6	63	0	0	0	0	1	2	0	0	0	0	0	1	2	4	2	2	0	0	0	0	7	35	17	137
7	1	0	1	4	1	11	3	5	28	1	0	0	2	0	8	38	73	102	61	39	5	0	0	0	384
8	0	0	1	9	31	19	45	34	10	6	32	161	301	328	435	526	530	615	614	565	299	228	199	252	5239
9	350	451	467	443	463	511	500	558	517	591	511	566	702	734	726	517	530	524	401	312	137	134	78	61	10785
10	102	75	88	68	30	37	2	284	588	676	702	715	729	219	514	287	40	72	189	294	143	130	196	313	6495
11	113	126	295	236	219	226	59	131	119	307	243	169	280	102	285	489	603	658	555	571	636	575	520	659	8175
12	507	422	411	477	307	619	734	700	555	631	574	290	262	123	169	35	12	51	44	28	51	17	8	0	7029
13	1	2	0	37	76	33	168	120	30	10	1	39	68	106	52	2	110	42	6	0	3	3	0	12	919
14	16	8	82	81	60	60	116	158	297	291	486	376	322	323	277	256	166	208	102	84	70	38	4	0	3880
15	1	1	53	79	217	168	189	210	325	314	198	354	518	504	614	670	550	622	546	442	89	259	285	350	7556
16	383	253	249	239	171	176	160	144	294	184	123	97	85	22	31	66	41	51	62	70	45	43	98	83	3170
17	58	46	12	63	146	376	411	536	565	446	404	198	366	378	525	586	500	438	424	681	612	224	210	622	8828
18	722	696	732	706	731	736	715	613	633	541	580	467	608	672	611	667	718	722	698	698	683	713	668	572	15901
19	681	554	544	678	719	740	603	572	518	610	644	700	731	725	695	680	696	725	727	616	465	405	543	741	15314
20	742	740	738	743	740	734	731	735	734	716	642	590	639	568	606	639	692	689	647	659	656	718	738	722	16558
21	709	732	719	729	715	633	697	675	590	668	664	711	691	735	732	732	691	732	719	583	630	677	686	593	16441
22	657	444	446	557	278	315	348	191	40	198	34	0	0	5	10	2	29	143	108	308	262	262	543	446	5625
23	584	586	374	403	613	636	615	552	560	650	665	681	672	684	661	687	686	586	639	695	646	677	688	651	14890
24	697	670	636	650	637	667	705	704	721	715	691	675	665	595	548	554	668	635	682	685	708	719	735	740	16100
25	742	735	719	710	711	706	709	702	694	711	722	683	565	490	244	156	36	3	0	0	2	21	83	278	10420
26	690	721	737	724	722	739	729	716	712	734	736	667	208	369	436	389	298	135	39	0	47	92	66	106	10813
27	252	175	243	297	334	395	469	500	480	551	504	590	567	500	432	299	414	359	372	148	260	389	559	503	9591
28	642	444	607	545	663	735	728	727	738	727	739	742	714	731	725	732	740	713	722	739	717	707	722	734	16730
29	709	737	727	729	729	720	739	744	741	737	667	596	213	90	73	21	2	0	0	3	15	35	197	79	9303
30																									
31																									

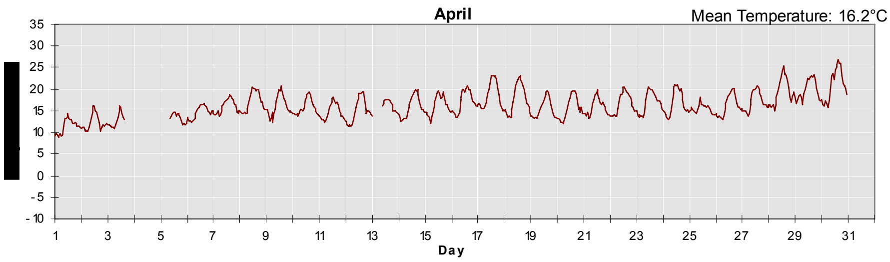
`WTprodT`: Table showing the hourly sum of the wind turbine energy production (kWh), per day of a month.



WT's energy production and mean wind speed per month

TempT - TempG

If in the `Input` worksheet, column numbers for the temperature were supplied, then in these 2 worksheets (similarly to the previous ones), one can find for each month the mean hourly temperature per day.

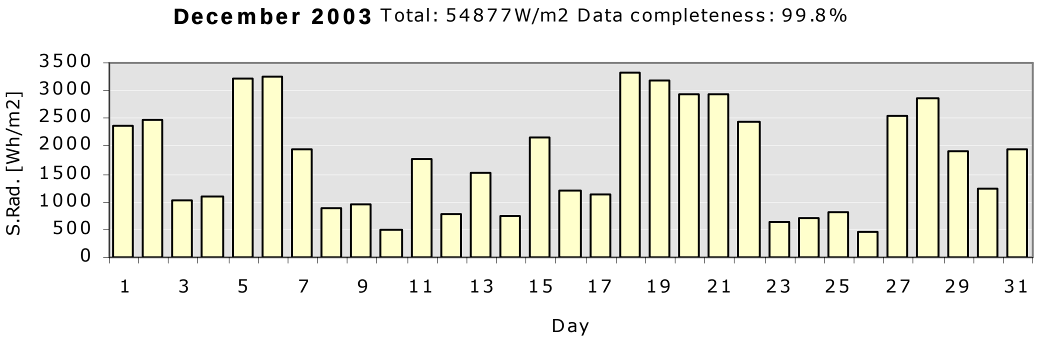


Variation of the mean temperature per hour, during 1-month period.
Note some missing data between 3 and 5 April.

SRadT - SRadG

Again, provided that in the `Input` worksheet, column numbers were specified for the solar radiation then, these 2 worksheets contain the sum of the hourly solar radiation per day, for each month of the year. Similarly to the above the tables and the graphs are in the `SRadT` and `SRadG` worksheets, respectively.

Some pyranometers (solar radiation measuring devices), record during the night, small negative values instead of zeros, due to a limited precision of their A/D converter. *WindRose* takes this into account by considering these data as zero, so that the correct hourly/daily sums are calculated.



Solar radiation daily sum during one-month period.
(worksheet: `SRadG`*).*

TempData Finally, in this worksheet the detailed information, which is indispensable for the all graphs appearing to all the above-mentioned worksheets is presented. In order to improve the readability of the sheet, the data are grouped in sets of columns of different colours. It is reminded here that, by double-clicking on the every Excel graph, the user can see the corresponding data columns, when selecting "*X-Values*" and "*Names and Values*". Moreover, new graphs can be created using all the listed data, which will be updated automatically each time the program runs.

CORRELATION – MISSING DATA PREDICTION

WindCorr

This worksheet uses the **MCP method** (*Measure, Correlate, Predict*) and deals with the correlation between the measured data at two different sites. Before using it, two files (one per site) have to be created, by running *WindRose* twice (setting two different file names, in `Input` sheet's appropriate cell). When done, the program runs by selecting the *Calculate Correlations* option, in the toolbar of the Excel's main menu.

Creating the necessary file for the Correlations (sheet `Input`*)*

Important Note

- The two measurement campaigns must contain data from a common time period. Otherwise, correlations cannot be calculated.

Based on the common data, calculations are performed to estimate *correlation coefficients (ρ)*, *linear regression coefficients (a, b* of the best-line fit*)* and the *goodness of fit (R^2)* [9]. All the above are calculated:

- per wind speed range and per direction sector
- per wind speed range but for all directions
- per direction, but for all the wind speeds (above calms)
- for all wind speeds, no matter the direction

It is reminded here that, correlation coefficient values close to 1.0 show similar (in-phase) variations, while values close to 0.0 show

[9] Goodness of fit : $R^2 = 1 - \frac{SSE}{SSM}$ with:

$$SSE = \sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2 \text{ and } SSM = \sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2$$

where: $\hat{y} = ax + b$ (a, b are the slope and the offset of the best-line fit)

Correlation coefficient:

$$\rho = \frac{\sum_{i=1}^{N}(x1_i - \mu_1)(x2_i - \mu_2)}{\sigma_1 \cdot \sigma_2}$$

, where $x1_{1,2,\ldots,N}$ and $x2_{1,2,\ldots,N}$ are the common data of the two time-series x1 και x2, with mean values μ_1 and μ_2 and standard deviations σ_1 and σ_2.

irrelevant variations (uncorrelated phenomena). Furthermore, goodness of fit values close to 1.0 show that the best-fit line represents very well the data *"cloud"* (using the linear regression coefficients).

Input parameters

The first column of the `WindCorr` sheet contains the necessary parameters for the program to run. The main input is 2 files containing the data from the Reference and the Target site. As pointed out earlier, these files are generated by running twice *WindRose* before this step. After running the *"Calculate Correlations"* command, the `WindCorr` sheet holds all the results in form of tables and graphs. Optionally, two files can be also created containing i) the concurrent pair of data and ii) the predicted time-series (see § below: Output Files). The remaining input parameters are:

- The initial time-shift of the 2 time-series, used to calculate the best possible correlation coefficient (see below: Methodology)[10].
- A Boolean value (*Yes/No*) indicating whether or not an hourly averaging will occur, before processing the data. Often, the hourly averaging provides better correlations.
- The number of the wind speed bins.
- The width of each wind speed bin.
- The minimum number of common hours that must exist (per wind speed bin and direction sector), in order to perform reliable calculations (recommended: 2hours, i.e. if the time step is 10min, 12 data)
- The number of the direction sectors (8, 12 or 16)[11].

Recommendation

When correlation results are not satisfactory, try less direction sectors, wider wind speed bins and hourly averaging.

[10] . For nearby sites 2 hours is sufficient, provided that the clocks are synchronized.

[11] Note that this number has nothing to do with the one set during the *WindRose* analysis.

Methodology

Consider correlating measured data from a Reference site (long-term data) and a Target site (short-term or incomplete data).

Sometimes nearby sites log wind data with a time lag, depending on their distance (and their data-loggers clock settings). This time lag can be determined by examining the correlation coefficient for various time-shifts *(i.e. -2h, -1h 50min, ..., 0, ... , +1h 50min, +2h)* of the Target time-series, in respect to the Reference ones. The time-shift, at which the maximum value of the correlation coefficient is found, is then inserted into the Target time-series (by adding it to its time/date array)[12] and displayed at the Table 2 of the `WindCorr` sheet.

Input File with the Reference time-series
c:\data\ref.bin
Input File with the Target (incomplete) **time-series**
c:\data\target.bin
Output File for the concurrent pairs of data (optional)
c:\data\sync.txt
Output File for of the predicted time-series (optional)
c:\data\pred.txt
Locate best correlation, by shifting Target series up to : [hours]
2
Transform time-series to :
1-hour data
Number of wind speed bins
20
Width of wind speed bin [m/s]
2
Min. hours of data per bin
2
Number of Dir. sectors
8
Correlation Method
y=ax

The input parameters of the `WindCorr` Sheet.

Time-shift values close to zero show that wind phenomena occur simultaneously to both sites. Global correlation coefficients close to

12 This step assures that time-series from data-loggers with unsynchronized clocks will be correctly processed !!

zero show uncorrelated phenomena and should alarm the user about the exploitation of the results.

Let's now assume, for simplicity reasons, that the Reference site holds 1-year long data and the Target site holds 9-month data (missing months: January, February and October). Hence the concurrent pairs of data are 9-month long.

The next step is to select the data of the Reference time-series that "*belong*" to a specific wind speed bin and direction sector. In the same time, we investigate their concurrent pairs from the Target time-series. For both data sets, all the statistical quantities (i.e.: mean values, linear regression coefficients, etc) are calculated and stored.

Now, if *WindRose* is asked to predict missing data, then for the wind speed it uses the regression coefficients and for the wind direction the difference of the mean direction values.

Arithmetic example: Assume 16 direction sectors and 2m/s wide wind speed bins. Suppose that 100 Reference time-series data have directions from the NNW sector (326.25° to 348.75°) and their wind speed falls into the [6m/s-8m/s) bin. The mean value of their directions is 330.5°, and their average wind speed is 7.2m/s. The corresponding concurrent (*simultaneous*) 100 data from the Uncompleted time-series (not necessarily within the [6m/s-8m/s) bin and the NNW sector) have an average wind speed of 8.4m/s (varying from 6.5m/s to 9.8m/s) and average direction 321° (varying from 315° to 327°). Therefore, for the wind speed, the slope and the offset of the linear regression are calculated as: α=1.022 and β=1.141 and for the wind direction, the difference of the means is: $\Delta\varphi = 321°-330.5° = -9.5°$

During the prediction phase, if in February the wind speed of the Reference site is u= 6.2m/s and the wind direction is φ=330° then, the predicted values (u', φ') for the other site are: $u' = \alpha u + \beta = 1.022*6.2 + 1.141 = 7.48$m/s and: $\varphi' = \varphi + \Delta\varphi = 330°-9.5° = 320.5°$

Similarly, the same procedure is followed for the correlation – prediction of the turbulence intensities. The predicted gust value is taken as:

Umax(predicted)=3*USDV(predicted).

Notes on the methodology example

- The correlation results depend on the common data period. Therefore, if the Reference time series were 5-

or 15 years long, the correlation results would be the same and based to the common 9-month period.

- Apart from the partial correlation results (per wind speed bin and per direction), global correlations are also calculated i.e.: **a)** per wind speed bin, no matter the direction, **b)** per wind direction for all wind speeds above calm.

- Assume that SSE wind directions appeared only during January (when no data exist for the Target time-series). Therefore, no correlation results exist and consequently the prediction will be based on the global correlation results (per wind speed bin, no matter the direction).

- Again, assume that only during October (another missing data period) extremely high wind speeds (>25m/s) occurred from the NNW direction. However, correlation results exist for the NNW direction but only up to 18m/s. Therefore, the predicted values of these high speeds will be based on the global NNW correlation results (i.e.: all the wind speeds above calms, from that sector).

Number of data	Data start at	Data end at	Mean(*) Wind Speed [m/s]	Number of concurrent data	Max. Wind Speed Correlation coefficient	at a time(**) shift [min]	Correlation Uncertainty for the Target site	General regression coefficients	of wind speeds	
4464	1/2/2000	2/3/2000 23:50	6.91				[m/s]	slope	offset [m/s]	R2
				4176	0.926	0	0.11	0.876	0.162	0.856
4176	1/2/2000 0:00	29/2/2000 23:50	6.21							

(*) of the 4176 concurrent data

(**) of Target site relative to Ref.site

General results of the Correlations (`WindCorr` sheet).

Output Tables

The 2nd table of the `WindCorr` sheet contains some statistics of the two input files and the global correlations results. In the beginning are given:

- The total number of the data in file.
- The dates of the first and last data points.
- The mean wind speed.

Then, in the next section are written:

- The number of the common data

- The maximum correlation coefficient after the time-shifting of the two-series (see above)
- The time-shift for which the max. Correlation coefficient occurred.

Finally, in the last section are written:

- The correlation uncertainty of the wind speed
- The global coefficients of the best-line fit (all wind speeds, no matter the direction)
- The goodness of fit R^2

The calculation of the correlation uncertainty is performed analytically, per each wind speed bin and direction sector of the Reference site, as follows:

$$correlation\ uncertainty = \frac{\sigma_u}{\sqrt{N}}$$

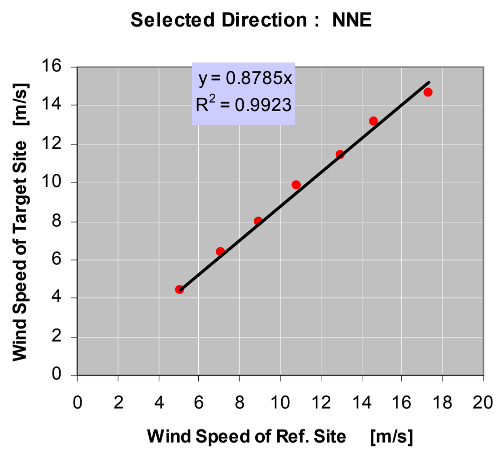
where: σ_u is the standard deviation of the (concurrent) wind speeds of the Target site and N the number of data per each interval. The displayed value is an average weighted value, based on the data wind speed and direction distribution.

The 3rd table of the `WindCorr` sheet presents the detailed correlation results, per direction and wind speed bin. Note that this is not a static table and its contents can change depending on the selected direction in the *drop-down* button.

Correlations Table. Select direction of the Reference Site: NNE

Wind speed bin - Ref. site [m/s]	Number of data	Wind Speeds: Ref. site Mean value [m/s]	Unc. site Mean value [m/s]	Correlation Coefficient	Slope	Offset [m/s]	R2	Directions: Ref. site Mean value	Unc. site Mean value	Turb.Intensities [%]: Ref. site Mean value	Unc. site Mean value	Corr. Coef.	Slope	Offset
0 - 2	51	1.15	0.17	0.4588	0.325	-0.204	0.21052	22	6	30.5	14.5	0.047	0.077	12.152
2 - 4	91	2.98	1.90	0.3883	1.097	-1.377	0.15078	22	2	20.6	40.6	0.464	2.350	-7.870
4 - 6	127	5.03	3.78	0.8789	1.004	-1.269	0.77246	22	11	14.8	18.8	0.626	1.057	3.154
6 - 8	147	6.97	5.58	0.6512	1.034	-1.631	0.42402	20	15	13.2	19.5	0.113	1.027	6.008
8 - 10	144	9.09	7.94	0.7379	1.251	-3.435	0.54443	20	17	13.2	15.8	0.501	0.773	5.663
10 - 12	137	10.98	9.79	0.2904	0.810	0.895	0.08434	19	15	14.5	14.0	0.165	0.336	9.118
12 - 14	101	12.97	11.29	0.1179	0.498	4.840	0.01391	19	23	14.9	13.3	0.205	0.430	6.856
14 - 16	58	14.98	13.84	0.7882	0.910	0.207	0.62122	17	22	15.1	12.9	0.778	0.954	-1.515
16 - 18	59	16.91	13.22	0.0480	0.453	5.563	0.00230	19	29	15.6	12.1	0.025	0.088	10.675
18 - 20	26	18.74	13.70	0.3194	3.609	-53.946	0.10204	18	27	15.5	11.3	0.070	0.207	8.056
20 - 22	18	20.78	14.46	0.2229	3.412	-56.440	0.04968	18	27	15.8	10.6	0.198	1.051	-6.007
22 - 24														
24 - 26														

The table with the detailed results of the correlations (`WindCorr` sheet). Note that the contents change according to the direction selection of the drop-down button.



Another result of the `WindCorr` sheet: Mean wind speeds correlation per direction sector.

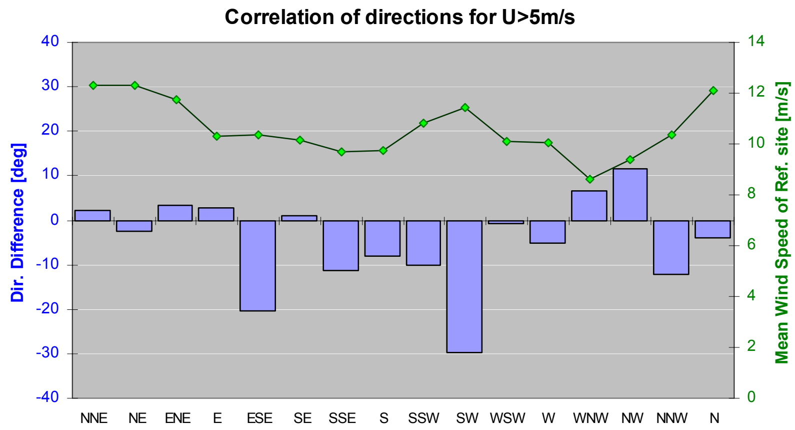
Output Files

Apart from the results presented in the worksheet's tables and graphs, three ASCII files are created containing the detailed results.

The 1st one contains the concurrent pair of data (i.e. in the above example 9-month data), which were used for the correlation/prediction.
The 2nd one includes time-series created by applying the calculated coefficients to the Reference time-series (in the given example, these are the 12-month long data). Note, that even if data existed in the time-series, there are not included.

The 3rd one is again the predicted data but <u>only</u> for the missing data period (i.e.: in the above example the predicted data for January, February and October).

Finally, the 4th table of the `WindCorr` sheet contains the correlation results per wind direction, for all wind speeds above 5m/s. Particular notice should be given to the angular shift of the wind direction vector.



A graphical representation of the Directions Correlation together with the mean wind speed (`WindCorr` sheet).

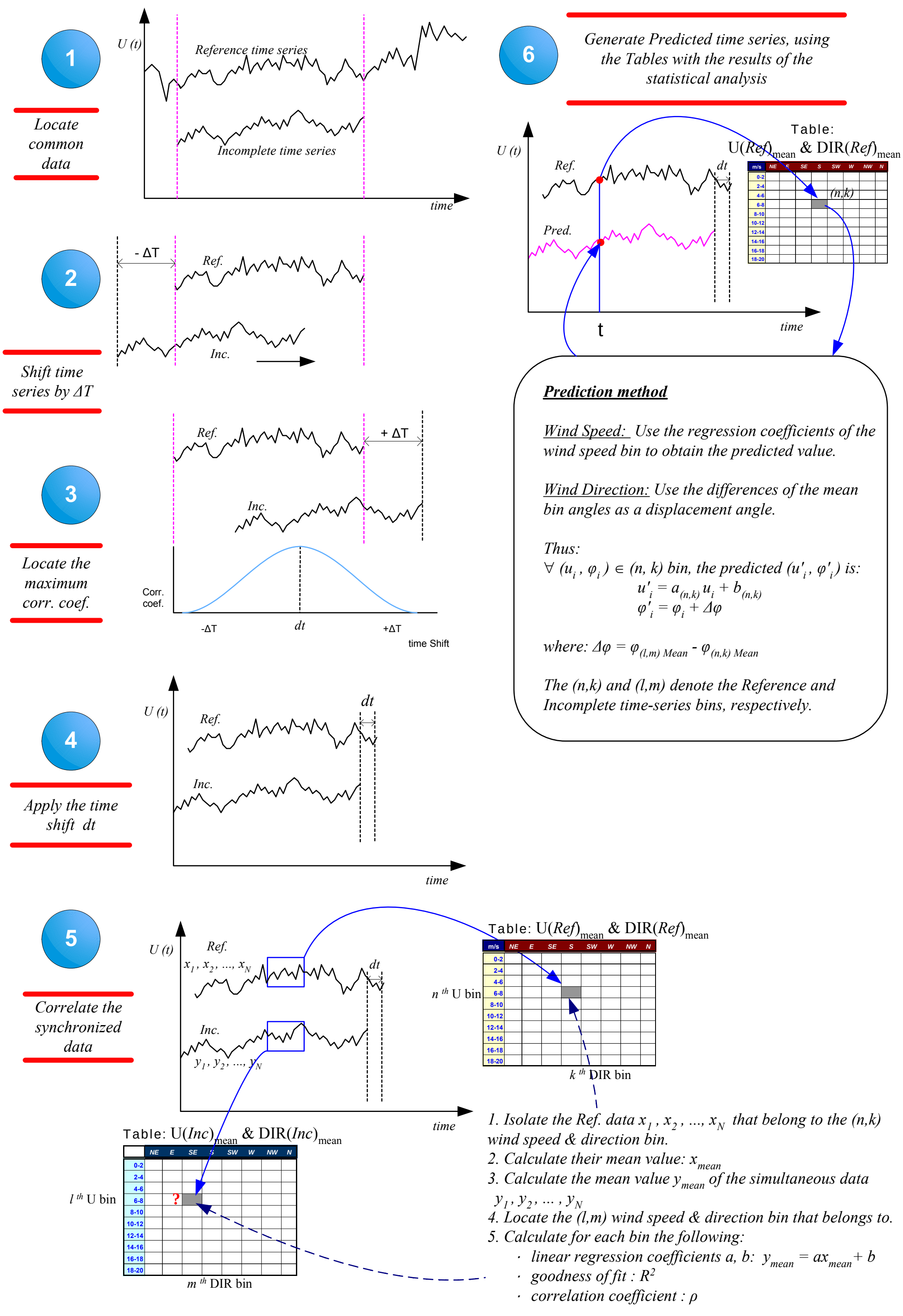
When averaging wind direction values, due to the discontinuity of the (0°, 360°) point, it is checked whether data exist in all the 4 quarters of the circle. In that case, results appear in red to remind that no reliable conclusions can be made.

Correlation of directions for wind speeds > 5m/s

Direction of Ref. Site	From	To	Number of data	Mean Direction of Ref. Site	Mean Direction of Unc. Site	Corr. Coeff.	Ref. site Mean wind speed	Unc. site Mean wind speed
NNE	11.25	33.75	552	19	19	0.2877	12.27	11.07
NE	33.75	56.25	65	40	38	0.1057	12.22	10.44
ENE	56.25	78.75	47	67	72	0.3424	11.57	9.58
E	78.75	101.25	31	86	92	0.2443	10.32	7.95
ESE	101.25	123.75						
SE	123.75	146.25	30	138	136	-0.2049	10.30	8.55
SSE	146.25	168.75	63	159	149	0.1365	9.69	8.39
S	168.75	191.25	83	181	172	0.4145	9.64	8.29
SSW	191.25	213.75	123	203	196	0.2704	10.79	8.98
SW	213.75	236.25	104	223	189	0.2810	11.34	9.81
WSW	236.25	258.75	49	248	243	0.3074	9.68	8.37
W	258.75	281.25	118	271	266	0.4507	10.09	9.69
WNW	281.25	303.75	58	290	298	0.5551	8.37	9.14
NW	303.75	326.25	44	318	333	0.3108	9.88	8.86
NNW	326.25	348.75	476	342	330	0.0900	10.39	9.04
N	348.75	11.25	1305	0	356	0.4160	12.07	10.88

(Red color: Mean values result from the 4 quarters of the trig. circle.)

Wind Direction correlations (`WindCorr` sheet).

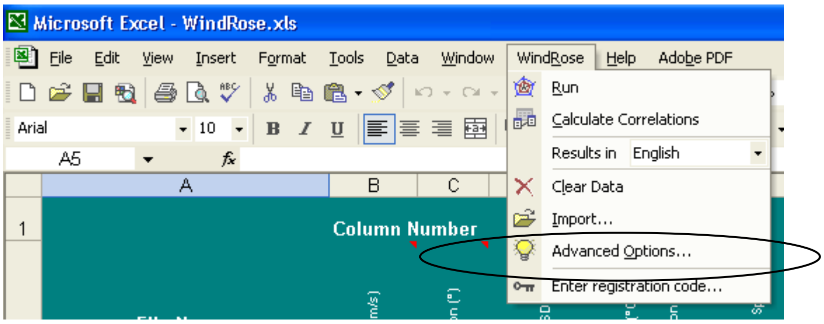


Methodology of the correlation – prediction procedure.

APPENDIX

Advanced Options Spike detection / Warnings, errors

The *"Advanced Options…"* menu of the *WindRose* includes various parameters which affect the program's behaviour but (most of the times) are not related to a specific site and consequently can be applied to several *WindRose.xls* files.



Changing the preset parameters of the WindRose program.

These parameters include among others: the acceptable limits of each quantity, the way spikes are detected, the tests to be performed to check "frozen" anemometers, etc. Most of them are straightforward and self-explanatory. After each run, they are all stored into the `TempData` sheet for traceability reasons. Consequently, it should be always possible to reproduce the same results, even if some of the advanced parameters were modified (they appear in red in `TempData` sheet).

When multiple anemometers are used, a check is performed between the (simultaneous) wind speed values per height. If "strange" values are noticed, then a warning or an error is produced and an entry is added into the Log file. They are based on the acquired experience and refer to each pair of successive anemometers and/or vanes. Note that, if a mast has 4 anemometers, then 3 successive tests will be performed for the anemometer pairs (1-2), (2-3) and (3-4). The alarm conditions are summarized below.

- Mean Wind Speed Vertical Profile $U2 / U1 < \varepsilon$
  - Warning: $\varepsilon = 1.2$
  - Error: $\varepsilon = 1.5$
- Max Wind Speed Vertical Profile $U2 / U1 < \varepsilon$
  - Warning: $\varepsilon = 1.8$
  - Error: $\varepsilon = 2.0$

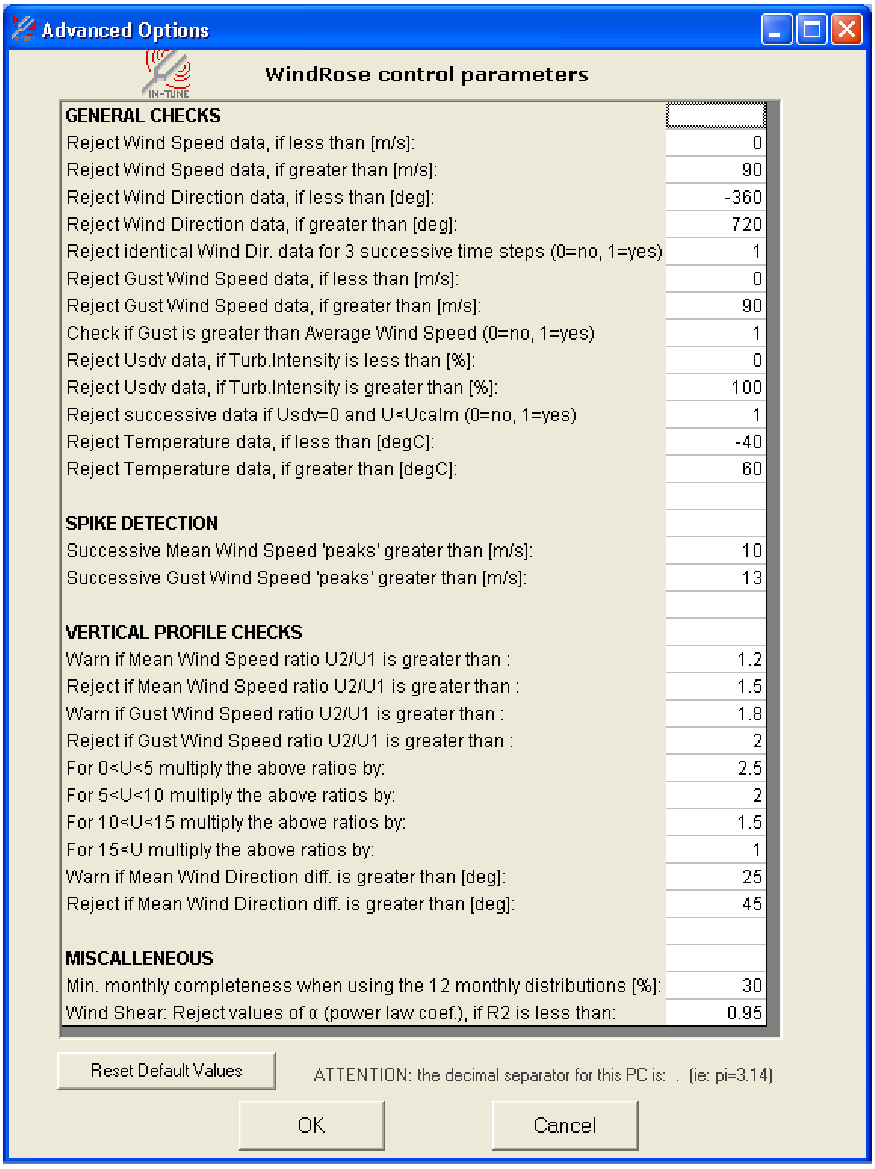
The final value of ε depends on the wind speed:

If $0<u<5$ then $\varepsilon=\varepsilon * 2.5$

If $5<u<10$ then $\varepsilon=\varepsilon * 2.0$

If $10<u<15$ then $\varepsilon=\varepsilon * 1.5$
If $15<u<65$ then $\varepsilon=\varepsilon * 1.0$

- Mean Wind Direction Vertical Profile $\Delta\varphi$ (for $U > 5$m/s)
  Warning: $\Delta\varphi = 25$deg
  Error: $\Delta\varphi = 45$deg
- Spike detection (for consecutive time steps)
  Umean: 10m/s
  Umax: 13m/s
- SDV constant or invariant during consecutive time steps.



GENERAL CHECKS	
Reject Wind Speed data, if less than [m/s]:	0
Reject Wind Speed data, if greater than [m/s]:	90
Reject Wind Direction data, if less than [deg]:	-360
Reject Wind Direction data, if greater than [deg]:	720
Reject identical Wind Dir. data for 3 successive time steps (0=no, 1=yes)	1
Reject Gust Wind Speed data, if less than [m/s]:	0
Reject Gust Wind Speed data, if greater than [m/s]:	90
Check if Gust is greater than Average Wind Speed (0=no, 1=yes)	1
Reject Usdv data, if Turb.Intensity is less than [%]:	0
Reject Usdv data, if Turb.Intensity is greater than [%]:	100
Reject successive data if Usdv=0 and U<Ucalm (0=no, 1=yes)	1
Reject Temperature data, if less than [degC]:	-40
Reject Temperature data, if greater than [degC]:	60
SPIKE DETECTION	
Successive Mean Wind Speed 'peaks' greater than [m/s]:	10
Successive Gust Wind Speed 'peaks' greater than [m/s]:	13
VERTICAL PROFILE CHECKS	
Warn if Mean Wind Speed ratio U2/U1 is greater than :	1.2
Reject if Mean Wind Speed ratio U2/U1 is greater than :	1.5
Warn if Gust Wind Speed ratio U2/U1 is greater than :	1.8
Reject if Gust Wind Speed ratio U2/U1 is greater than :	2
For 0<U<5 multiply the above ratios by:	2.5
For 5<U<10 multiply the above ratios by:	2
For 10<U<15 multiply the above ratios by:	1.5
For 15<U multiply the above ratios by:	1
Warn if Mean Wind Direction diff. is greater than [deg]:	25
Reject if Mean Wind Direction diff. is greater than [deg]:	45
MISCALLENEOUS	
Min. monthly completeness when using the 12 monthly distributions [%]:	30
Wind Shear: Reject values of α (power law coef.), if R2 is less than:	0.95

List of the Advanced Options of the WindRose program.

Examples of the *WindRose* log file when an error occurs:

```
16/07/2004 14:30 Umax Error:
Value beyond the error limit for the vertical profile

Umax(45m)=39.41 Umax(30m)=12.55, while:
Umean(45m)=7.51 Umean(30m)=6.98

File: c:\data\site1.txt Line: 21742
```

```
01/07/2000 21:00 Dir Error:
Values beyond the error limit for the vertical profile
Dir1= 230.0 Dir2= 329.3, while:
Umean(45m)=10.64 Umean(30m)=9.93
Umax(45m)=13.76 Umax(30m)=12.87

File: c:\data\site1.txt Line: 5334
```

Air density variation with height

WindRose expects power curves (given in the `PowerCurve` sheet) to be normalized, as recommended by IEC (sea level, 15°C, 1013.25mbar). At higher altitudes and different temperatures, air-density varies considerably and its calculation has to be done accurately, since it influences significantly the energy calculations.

Ideally, for accurate air density measurements, atmospheric pressure, temperature (and relative humidity) have to be measured simultaneously with the wind speed. In the opposite case, 3 empirical methods are used to deduce the air density. Analytically:

Case A: using atm. pressure and temperature data

Usually, atmospheric pressure is measured at a low height (ie: data logger level, assumed value: H_{baro}=2m), thus B_{meas} data are "extrapolated" to hub height H_{hub}, according to the following formula:

$$B_{corr} = B_{meas} + 1013.25 \cdot \left[\left(1 - 2.25577 \cdot 10^{-5} \cdot H_{hub}\right)^{5.25588} - \left(1 - 2.25577 \cdot 10^{-5} \cdot H_{baro}\right)^{5.25588} \right]$$

Then, the air density can be calculated using the following equation:

$$\rho = \frac{B_{corr}}{R \cdot T} - \frac{\phi \cdot 0.378 \cdot P_w}{R \cdot T}$$

where: R=287 Joule deg^{-1} kg^{-1} , T is the measured temperature (in °K), φ the relative humidity και P_w the vapor pressure (in hPa). The last depends on the temperature and is calculated as follows:

$$P_w = 2.05 \cdot 10^{-7} \cdot e^{0.0631846 \cdot T}$$

Finally, if relative humidity φ data are not available, then a constant value of 0.5 (50%) is assumed.

Case B: Atm. pressure time-series not available

When atm. pressure is not recorded, then air-density estimation due to the height (site elevation + anemometer height) can be done as follows, depending on the user's selection (`Input` sheet, 4th Table):

1st Method

This method, mainly used when temperature and pressure measurements are not available, employs an empirical formula in which air density is a function only of the height [m] from the sea level:

$$\rho = 1.226 \cdot e^{-3.1089 \cdot 10^{-5} \cdot Height}$$

2nd Method

Another method assumes the atmosphere's adiabatic variation, therefore:

$$\frac{dp}{dz} = -g\rho$$

where g=9.81m/s² is the gravity acceleration, ρ the air-density and z the height. Using the ideal gas equation:

$$p = R\rho T$$

where R=287 Joule deg^{-1} kg^{-1} is the gas constant, p the atmospheric pressure and T the temperature in Kelvin [°K], we obtain:

$$\frac{dp}{p} = -\frac{g}{RT}dz$$

Assuming that the temperature T varies with height:

$$T = T_0 - \Gamma z$$

With T_0 = 288°K (=273+15) and Γ is the vertical temperature gradient usually taken as: 6.5°K/km.

Integrating the above equation:

$$\int_{p_0}^{p} \frac{dp}{p} = -\frac{g}{R}\int_0^z \frac{dz}{T_0 - \Gamma z}$$

and taking the logarithm:

$$\ln\frac{p}{p_0} = \frac{g}{R\Gamma}\ln\left(1 - \frac{\Gamma z}{T_0}\right)$$

We, finally, conclude to the equation:

$$\rho = \rho_0 \frac{T_0}{T}\left(1 - \frac{\Gamma z}{T_0}\right)^{\frac{g}{\Gamma R}}$$

that relates the air density to the temperature T and the height z of a site. Note that, if the ASCII data files do not contain temperature columns, then a mean temperature value for the measurement period has to be set in the fourth table of the `Input` sheet.

At the end of the document a comparison table is given showing the differences of the first two methods.

3rd Method

This method uses 12 preset values, one per each month of the year. These values can be retrieved either from a nearby meteorological station or set intuitively.

Weibull distribution

The probability density function $f(u)$ of the Weibull distribution is given by the formula:

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^{k}} \quad \{1\}$$

where k and C are the characteristic parameters of the distribution. Two methods exist for the calculation of these parameters:

1st Method: Using only the Mean and SDV values

Solving {1} for k and C, requires that the mean value μ and the standard deviation σ must be expressed as a function of k and C.

From the mean-value definition:

$$\mu = \mathrm{E}(u) = \int_0^\infty u f(u) du = \int_0^\infty u \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^{k}} du$$

Using the transformation $t = \left(\frac{u}{c}\right)^k$ we obtain:

$$u = ct^{\frac{1}{k}} \text{ and } \left(\frac{c}{k}\right)dt = \left(\frac{u}{c}\right)^{k-1} du$$

Therefore:

$$\mu = \int_0^\infty u \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^{k}} du = c\int_0^\infty t^{\frac{1}{k}} e^{-t} dt$$

Recalling the gamma function definition:

$$\Gamma(q) = \int_0^\infty t^{q-1} e^{-t} dt \text{ , } q > 0$$

we deduce that:

$$\mu = c\Gamma\left(1+\frac{1}{k}\right) \qquad \{2\}$$

Now, for the standard deviation σ is valid to write:

$$E\left\{(u-\mu)^2\right\} = \sigma^2 = E\left(u^2\right) - \mu^2$$

Following the same transformation, we have:

$$E\left(u^2\right) = c^2\Gamma\left(1+\frac{2}{k}\right)$$

So, finally we conclude:

$$\sigma^2 = c^2\left\{\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right\} \qquad \{3\}$$

The Weibull distribution in its cumulative form $P(u \le u_1)$ is written as:

$$P(u \le u_1) = \int_0^{u_1}\left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^k} du$$

or:

$$P(u \le u_1) = 1 - e^{-\left(\frac{u_1}{c}\right)^k} \qquad \{4\}$$

The following asymptotic series is used as good approximation of the gamma function Γ:

$$\Gamma(x) = x^{(x-0.5)} e^{-x}\sqrt{2\pi}A(x) \qquad \{5\}$$

where:

$$A(x) = 1 + \frac{a_1}{x} + \frac{a_2}{x^2} + \frac{a_3}{x^3} + \frac{a_4}{x^4} + \cdots$$

with : $a_1 = \frac{1}{12}, a_2 = \frac{1}{288}, a_3 = -\frac{139}{51840}, a_4 = -\frac{571}{2488320}\cdots$

Dividing {2} and {3} and setting $x = \frac{1}{k}$ we finally obtain the following non-linear x-function:

$$g(x) = \frac{\Gamma(1+2x)}{\Gamma^2(1+x)} - 1 - \left(\frac{\sigma}{\mu}\right)^2 = 0$$

Resolving $g(x) = 0$ is achieved by applying the Newton iterative method, starting from an initial value. For the (v) iteration we can write:

$$x^{(\nu)} = x^{(\nu-1)} - \frac{g^{(\nu-1)}}{g'^{(\nu-1)}}$$

Its 1st x derivative of *g(x)* is:

$$g' = \frac{\partial g(x)}{\partial x} = \frac{\Gamma'(1+2x)\Gamma(1+x) - 2\Gamma(1+2x)\Gamma'(1+x)}{\Gamma^3(1+x)}$$

where $\Gamma'() = \frac{\partial \Gamma()}{\partial x}$

The gamma function's derivative $\Gamma'(x)$ is calculated using the relationship $\left(x^x\right)' = x^x\left(\ln x + 1\right)$ that finally gives:

$$\Gamma'(x) = \frac{B(x) - \Gamma(x)}{x}$$

Using {5}, that is the asymptotic approximation of the Gamma function, leads to the following form for the $B(x)$ function:

$$B(x) = \sqrt{2\pi x}\; x^x e^{-x} \left\{ A(x)\left[\frac{1}{2x} + \ln x\right] + \frac{\partial A(x)}{\partial x} \right\}$$

Keeping just the first 4 terms we obtain:

$$B(x) = \sqrt{2\pi x}\; x^x e^{-x} \left\{ A(x)\left[\frac{1}{2x} + \ln x\right] - \frac{a_1}{x^2} - \frac{2a_2}{x^3} - \frac{3a_3}{x^4} \right\}$$

As a result, *B(x)* is approximated permitting the calculation of the *g'(x)* at the v^{th} iteration.

2nd Method: Using the data distribution (Weibull paper)

This method (also referred as "Weibull paper") can be applied only if the wind speed distribution is already known.

The cumulative form of the Weibull distribution (i.e.: the probability that the wind speed is greater than a given value) is written as:

$$Q\left(u \geq u_1\right) = e^{-\left(\frac{u_1}{c}\right)^k}$$

Taking twice the logarithm, we obtain:

$$ln[\, - ln(Q(\mathrm{u})\,] = \mathrm{k}\; ln(\mathrm{u}) - \mathrm{k}\; ln(\mathrm{C})$$

Therefore, if we plot a graph with the X and Y axes to be *ln*(u) and *ln*[- *ln*(*Q*(u)] respectively, then the Weibull distribution becomes a straight line with slope *k* and intercept point to Y-axis the quantity: -k *ln*(C), from which the *C* parameter can be calculated.

Note that, in the `Input` sheet it is given the possibility to "restrict" the wind speed range in which the fit is performed, so that extreme values (accentuated by the logarithms) will not affect the results. It is suggested to fit the data within the range: 4-16m/s.

Power Curve correction

Following the IEC-61400-12 recommendations, the power curve is *corrected* depending the power control (stall, pitch control) of the wind turbine. The formulas used are the following:

A/Γ stall control: $$P = P_{norm} \cdot \frac{\rho}{\rho_{norm}}$$

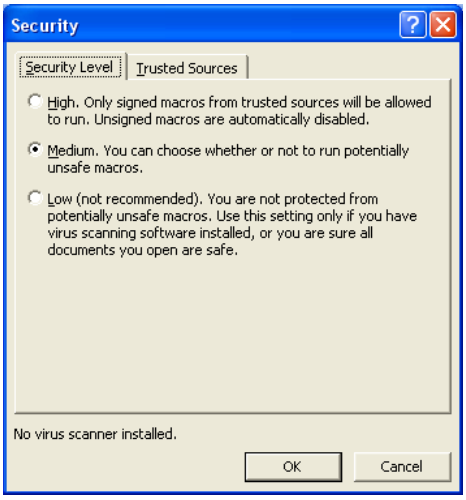
A/Γ pitch control: $$U = U_{norm} \cdot \left(\frac{\rho}{\rho_{norm}} \right)^{-\frac{1}{3}}$$

INSTALLATION ISSUES

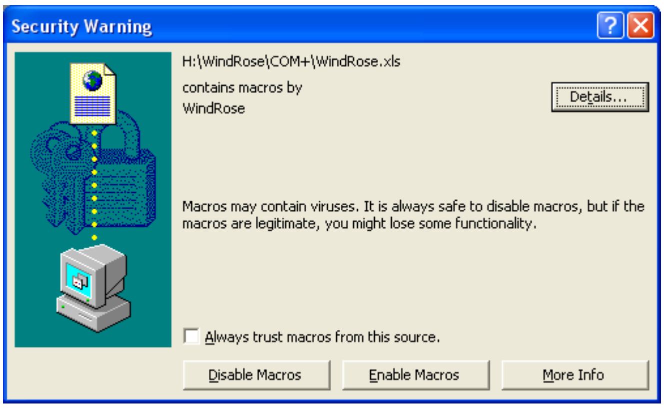
WindRose.XLS Security Warning

Under certain configurations (i.e.: Office XP and/or Windows XP professional), you may not be able to open the *WindRose.XLS* file with the included macro enabled. This will prevent *WindRose* to function properly. The following steps need to be taken to overcome this situation. The purpose is to end up with the *WindRose* macro to be among the Microsoft Excel's trusted sources.

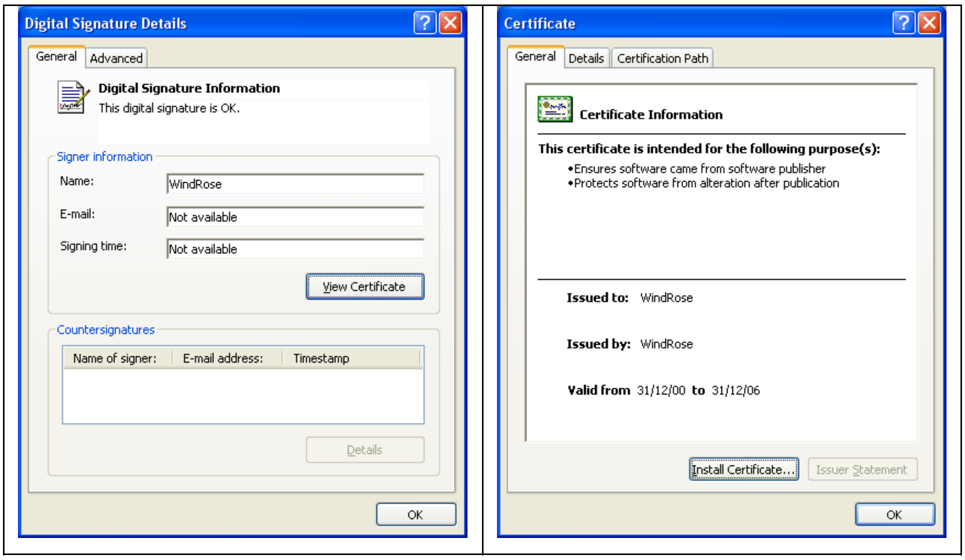
Therefore, open Excel (without *WindRose.XLS*). go to *Tools*, *Macro*, *Security*. Set it to Medium.



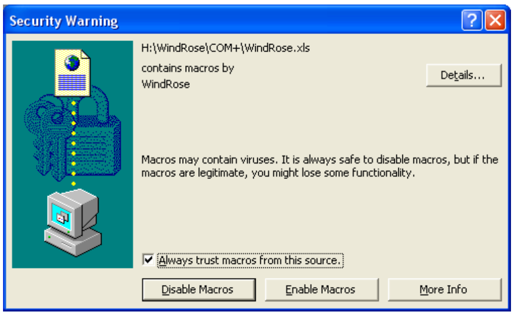
Now, open *WindRose.XLS*. A security warning appears. Choose *Details….*



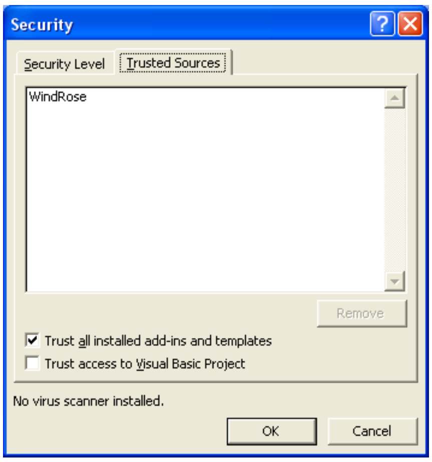
Then, select *View Certificate* and afterwards *Install Certificate.*



Now, come back to the previous screen, where the *Enable Macros* option is not anymore grayed (if not close Excel and re-open WindRose.XLS). Then, check the box *Always trust macros from this source*. Click *on Enable Macros* and start working with WindRose.XLS.



Finally, you may check that *WindRose* is among Excel's *Trusted Macros*. Moreover, you may re-set the Security Level to *High*.



REFERENCES

1. IEC-61400-12 International Electrotechnical Commission, "*Wind Turbine Generator Systems, Part 12: Wind turbine Power Performance Testing*", 1997.

2. "*Introduction to Wind Energy*", E.H. Lysen, CWD, May 1983, The Netherlands.

3. "*Atmospheric turbulence. Models and Methods for Engineering Applications*", H. Panofsky, J. Dutton, John-Wiley & Sons, 1984.

4. "*Structure of Atmospheric Boundary layer*", Z. Sorbjan, Practice hall, 1989, USA.

5. "*Weibull coefficients estimation*", D. Douvikas, Centre for Reneable Energy Sources (CRES), June 1999.

6. "*Wind data analysis* ", D. Foussekis, CRES, April 1994.

7. "*Wind Energy Conversion Systems*", L. L. Freris, Prentice Hall, 1990

8. "*Atmospheric Science, An Introductory survey*", John. M. Wallace, Peter V. Hobbs, Academic Press, Inc. 1997.

Air-Density [kg/m^3] as a function of Elevation. Comparison of the 2 methods (Case B)

Method 1	Height	Method 2 — Temperatures [°C]									
		-10	-5	0	5	10	15	20	25	30	35
1.226	**0**	1.341	1.316	1.292	1.269	1.247	1.225	1.204	1.184	1.164	1.145
1.222	**100**	1.329	1.304	1.280	1.257	1.235	1.213	1.193	1.172	1.153	1.134
1.218	**200**	1.316	1.292	1.268	1.245	1.223	1.202	1.181	1.161	1.142	1.123
1.215	**300**	1.304	1.280	1.256	1.233	1.211	1.190	1.170	1.150	1.131	1.112
1.211	**400**	1.292	1.267	1.244	1.221	1.200	1.179	1.158	1.139	1.120	1.101
1.207	**500**	1.280	1.255	1.232	1.210	1.188	1.167	1.147	1.128	1.109	1.091
1.203	**600**	1.267	1.243	1.220	1.198	1.177	1.156	1.136	1.117	1.098	1.080
1.200	**700**	1.255	1.232	1.209	1.187	1.165	1.145	1.125	1.106	1.087	1.069
1.196	**800**	1.243	1.220	1.197	1.175	1.154	1.134	1.114	1.095	1.076	1.059
1.192	**900**	1.232	1.208	1.186	1.164	1.143	1.122	1.103	1.084	1.066	1.048
1.188	**1000**	1.220	1.197	1.174	1.152	1.132	1.112	1.092	1.073	1.055	1.038
1.185	**1100**	1.208	1.185	1.163	1.141	1.121	1.101	1.081	1.063	1.045	1.027
1.181	**1200**	1.197	1.174	1.151	1.130	1.110	1.090	1.071	1.052	1.034	1.017
1.177	**1300**	1.185	1.162	1.140	1.119	1.099	1.079	1.060	1.042	1.024	1.007
1.174	**1400**	1.174	1.151	1.129	1.108	1.088	1.068	1.050	1.031	1.014	0.997
1.170	**1500**	1.162	1.140	1.118	1.097	1.077	1.058	1.039	1.021	1.004	0.987
1.167	**1600**	1.151	1.129	1.107	1.087	1.067	1.047	1.029	1.011	0.994	0.977
1.163	**1700**	1.140	1.118	1.096	1.076	1.056	1.037	1.019	1.001	0.984	0.967
1.159	**1800**	1.129	1.107	1.086	1.065	1.046	1.027	1.008	0.991	0.974	0.957
1.156	**1900**	1.118	1.096	1.075	1.055	1.035	1.016	0.998	0.981	0.964	0.948
1.152	**2000**	1.107	1.085	1.064	1.044	1.025	1.006	0.988	0.971	0.954	0.938
1.149	**2100**	1.096	1.074	1.054	1.034	1.015	0.996	0.978	0.961	0.945	0.928
1.145	**2200**	1.085	1.064	1.043	1.024	1.005	0.986	0.968	0.951	0.935	0.919
1.141	**2300**	1.075	1.053	1.033	1.013	0.994	0.976	0.959	0.942	0.925	0.910
1.138	**2400**	1.064	1.043	1.023	1.003	0.984	0.966	0.949	0.932	0.916	0.900

Comparison of the first two methods for the air-density variation with height.