Context and purposes

The SWIP project (‘New innovative solutions, components and tools for the integration of wind energy in urban and peri-urban areas’) aims to expand the market for Small Wind Turbines in Europe by developing, implementing and testing innovative solutions and components to improve performance, reduce maintenance costs, and encourage integration of turbines into urban and peri-urban areas. This European Project combines the efforts of thirteen partners in ten countries, from different technical fields of interest: energy, wind, mechanics, aerodynamics, sound.

Within this project, the wind fields have been characterized in order to feed the different aspects of the development of three pilot sites. The aim of this paper is to describe this process, with two objectives:

- Focus on the different sources of Wind data (Eurocode, public meteo station, on site measurements), and the different tools to characterize the wind (from wind roses to spectral analysis)
- Focus on the use of these characteristics (wind resource assessment, choice of technical solutions for wind turbines, anchorage and mast design, sound production and propagation, hypothesis for blade aerodynamics,…)

Wind characteristics

Different sources of data can feed the process of wind characterization. Six levels of sources are described here, from the most general and cheapest, to the most specific and expensive.

1. Public codes

In European countries, high winds are well described by Eurocode I (NF-EN-1991-1-4) and its national annexes. It defines the maximum mean wind speeds, with a 50-years return period, thanks to a map (base wind speed at 10m, about 22m/s to 30 m/s depending on the region in Europe), and a vertical profile. This profile is governed by a logarithmic law with a roughness length parameter depending on the surrounding (ground occupation). These vertical profiles define the mean wind speed and the turbulent intensity by the formulae:

$$V(z) = V_0.\ln\left(\frac{z}{z_0}\right)$$

$$I(z) = \frac{1}{\ln\left(\frac{z}{z_0}\right)}$$

(some details can vary from a country to another).

Note that this definition can also give a first estimate of the wind shear (in open area, *ie* with no obstacles). The wind shear is a way to characterize the local vertical gradient of the wind speed. Given two different heights :

$$\alpha = \frac{\ln\left(\frac{V(H_2)}{V(H_1)}\right)}{\ln\left(\frac{H_2}{H_1}\right)}$$

Annex B of Eurocode also defines the power spectrum of the wind speed:

$$S_L(\nu) = \frac{\nu . SPD(\nu)}{\sigma^2} = \frac{6.8 \, . f_L}{(1 + 10.2 \, . f_L)^{5/3}}$$

$$f_L = \frac{\nu . L_T}{U}$$

This power spectrum depends on a parameter called “turbulent length scale”. This turbulent length scale depends on the altitude and the local roughness; it can be estimated by the formula:

$$L_T(z) = 300 \left(\frac{z}{200}\right)^{0.67+0.05\ln(z_0)}$$

Other codes, such as IEC 61400-1 or IEC 61400-2, have other similar definitions (for both wind speed, turbulent intensity, even length scale). Note that different codes define different parameters for the spectral analysis of wind speed: Λ for high frequency turbulence only (IEC 1 and 2), L for Kaimal spectrum (IEC 1 and 2), L_i for Van Karman isotropic model (IEC 2), $L_T(z)$ for modified Kaimal spectrum (Eurocode). Later in this paper, we will rely only on this last definition.

2. From public meteo station

World Meteorological Organization collects and dispatches some meteorological measurements all over the world. The National Climatic Data Center (NCDC, from National Oceanic and Atmospheric Administration in United States) maintains the Climate Data Online portal[1]. This is a useful tool to recover the long term measurement from any WMO meteorological station.

For instance, the ten years wind speed and direction are analyzed: wind speed distribution and wind roses. The wind potential $p = \frac{1}{2}\rho V^3$ is analyzed using the same tools.

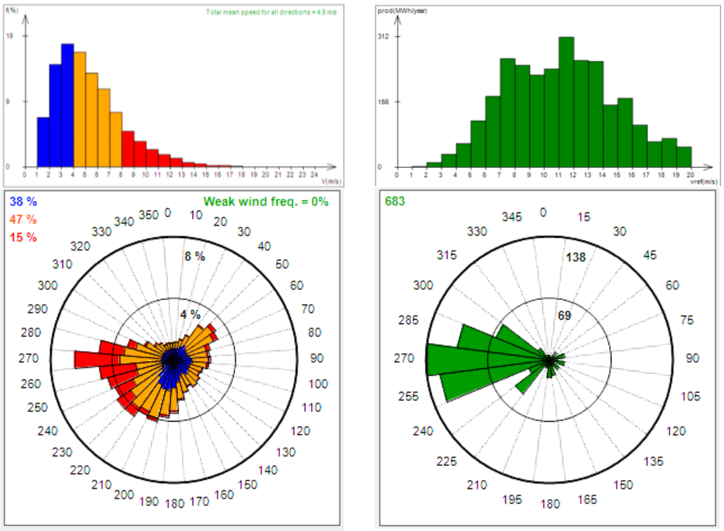

Figure 1: distribution (top) and rose (bottom) of wind speed (left) and wind potential (right)

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[1] http://www.ncdc.noaa.gov/cdo-web/

Note that this data corresponds only to the meteo station. The information can be transposed to the wind turbine position using the log-law profile (at the same location), linear models (WaSP for instance) in flat terrain, CFD codes (*e.g.* Meteodyn WT) in complex terrain.

3. From simple local measurements

In order to achieve more specific results, one has to install its own meteorological mast at the wind turbine location. In the example of SWIP project first pilot site (Choczewo), this mast is installed close to the parapet on a building roof, where a small wind turbine is supposed to be installed.

Figure 2: mast installation in Choczewo pilot site

Note that in this case, the installation is quite rich with two cup anemometers, one wind vane, and one sonic anemometer. Generally speaking, the minimum installation deals only with one cup anemometer and one wind vane. These measurements are recorded once over 10 minutes, including their variations (standard deviation).

These measurements give global wind speed characteristics: annual mean value, distribution (binned or Weibull parameters). The time stamp analysis can reveal a diurnal effect.

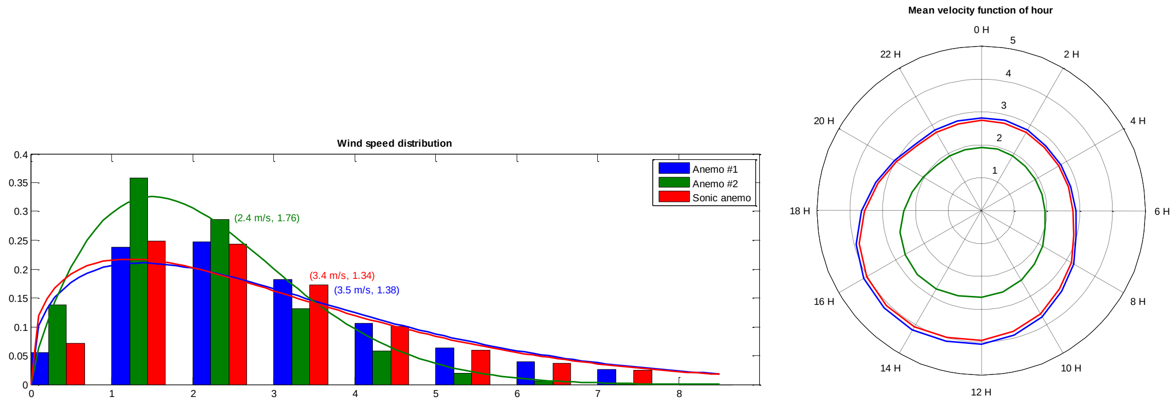


Figure 3: First analysis of local measurements

Wind and potential roses can confirm/invalidate the results from meteo-station data.

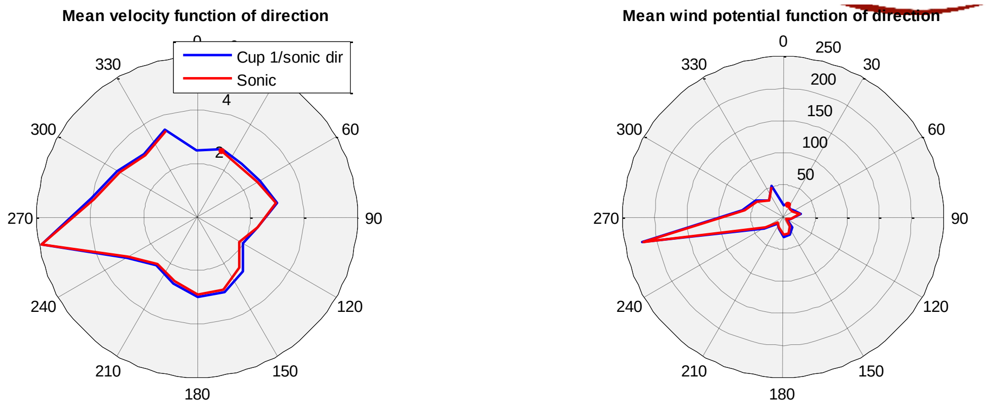


Figure 4: wind speed (left) and potential (right) roses from local measurements

The turbulence level is given by the formula:

$$I\% = \frac{\sigma_u}{\overline{U}} = \frac{u_{rms}}{\langle U \rangle}$$

It can be analyzed by direction, and/or time stamp (diurnal effect), etc…

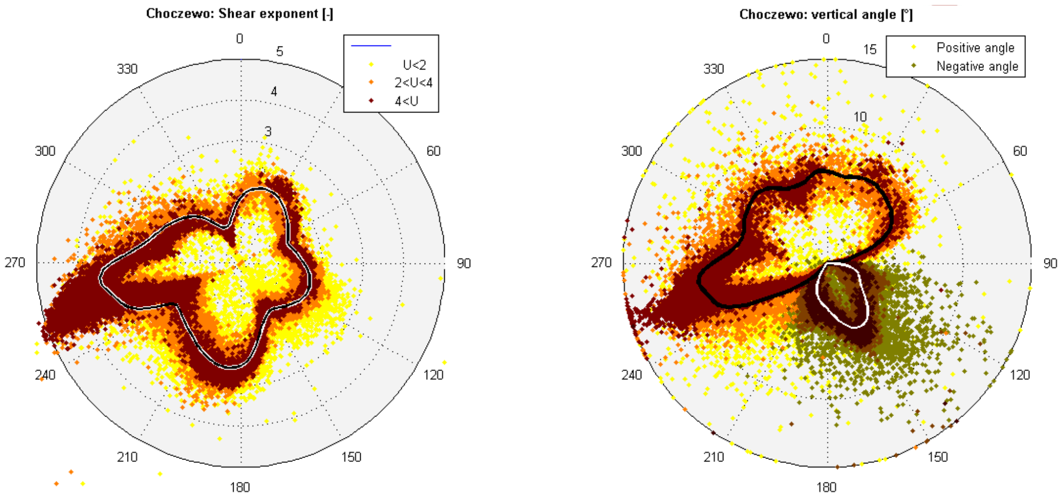
4. From complex local measurements

More complex installations use several anemometers to characterize deeper the wind flow.

Figure 5: mast installation in Zaragoza pilot site

More precisely, one can install two anemometers and two wind vanes at two different heights, in order to measure the wind shear (vertical profile of wind speed) and wind veer (vertical profile of wind direction), also named twist.

3D anemometers, such as Sonic, provides also the vertical component (or vertical deviation) of the wind flow. All these parameters (shear, veer, vertical deviation) have to be analyzed depending on the wind incidence.



Choczewo: Shear exponent [-]

Choczewo: vertical angle [°]

Figure 6: Example of Shear and vertical deviation analysis, depending on the incidence

5. From high frequency measurements

In order to go deeper in the analysis, the measurement process has to be updated. This concerns the sampling frequency of analog signals: to deal with wind turbulence, one has to raise the sampling frequency up to one hertz. This results on a large data set, with poor information (within small winds, it is very difficult to make a correct spectral analysis). Thus, a valid strategy is to measure only 2 hours samples, triggered by the mean wind speed (with a threshold value depending on the wind characteristics of the site; in the example of figure 3, a correct threshold value may be 4 m/s). There are several goals to achieve: keep low frequencies in the signal (10 minutes are not long enough to measure low frequencies), reduce the total amount of data, keep only the high wind speeds where the signal-to-noise ratio is better. Note that with the increasing storage capabilities, another strategy is to measure the whole year at 1Hz sampling frequency, and operate the selection of high wind “events” later on (within the whole year signal). The first strategy is more complicated (programming data logger), but cheater in storage terms.

Then, each event has to be analyzed through Fourier transforms. Then, applying a pick-picking detection and curve fitting algorithm, one can identify the turbulent length scales.

Generally speaking, turbulent length scales depend on the wind incidence. Thus, it is difficult to achieve a complete description because of the lack of “high wind events” in some wind sectors.

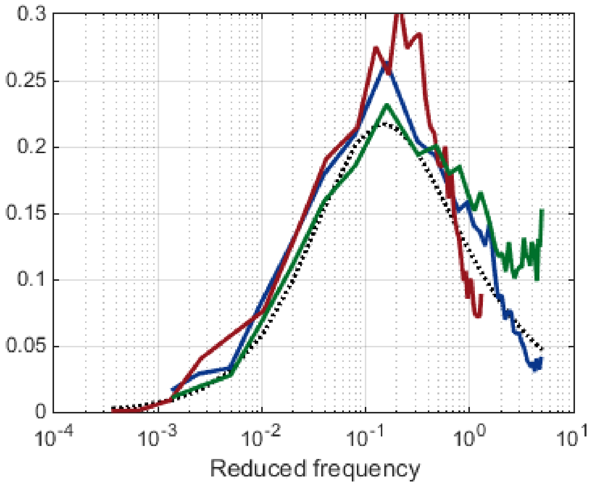


Figure 7: Example of turbulent length scale identification.
Black dotted: modified Kaimal spectrum. Three colored lines: three anemometers power densities

When different height anemometers are measured synchronously at high frequency, the instant shear can be analysed. The instant shear is here defined by the instant difference of wind speeds measured at different heights:

$$\delta v(t) = v_2(t) - v_1(t)$$

This instant shear is also analyzed throught Fourier transform.

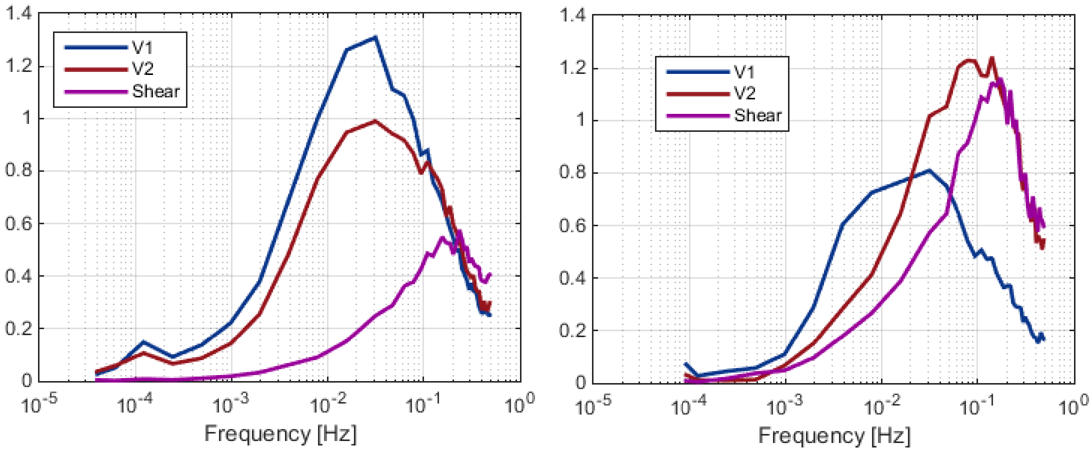


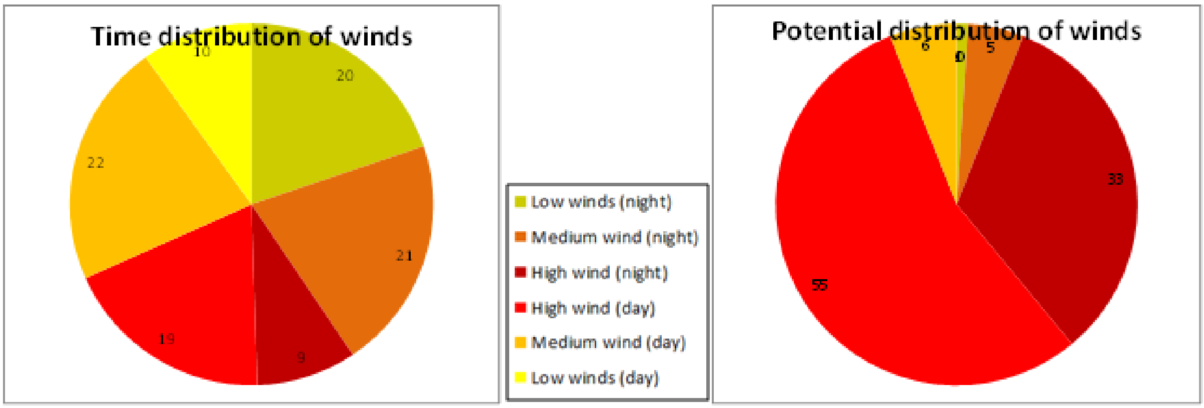
Figure 8: Example of instant shear analysis
Left: normal behavior. Right: detached flow behavior

Figure 8 shows two example of such an analysis. On the left, the two anemometer spectra (blue and red) have similar shape with different amplitudes: instant shear has much higher frequencies and much lower amplitude: this means that most of the variations of wind speed are well correlated and in-phase. On the opposite, the right figure shows a behavior (both in amplitude and in frequencies) that departs from the anemometer spectra: the instant shear is much higher than in previous case. This means that the two cup anemometers measure different and uncorrelated winds: in this case, the flow is detached and V_2 is in the parapet's wake.

6. Wind models

Crossing all these info, one can construct a wind model with different regimes. Here, we present a model with 3 regimes:

CHOCZEWO	Small winds	Medium winds	High winds
Speed limit	0 to 2 m/s	2 to 4 m/s	above 4m/s
% of time	29%	43%	28%
% of potential	1%	11%	88%
Mainly during…	night	equal	day
Direction	All around	E-E-N-E W-W-S-W	W-W-S-W
Turbulence	30%	30%	25%
Mean Shear α	1.7	1.4	3.5
Upflow angle	Variable From -5° to +7°	0°	+9°
Twist	0 to 5°	0° to 3° /m	Variable +/- 6°/m
Turbulent Length scale	-	25m/50m	10m/90m Detached flow
Instant Shear amp.	-	0.7σ	$1.\sigma$
Instant Shear freq.	-	0.2 Hz	0.2Hz



Dispatch of wind models to partners

- Wind resource assessment

The typical target when we set up a wind measurement campaign is to obtain an energy estimate. This is calculated from wind speed, wind direction, and turbulence intensity. Note that other physical parameters (not wind) are also needed (temperature, Humidity, Pressure). In addition, the temporal representativeness of the available data is very important in order the get its characterization. In this way, annual measurement campaigns must be developed, including a long-term analysis if possible. This is very important if we want to ensure that the expected energy production during the next years has been properly estimated.

- Electrical dimensioning

In order to provide an optimal permanent magnet synchronous generator (PMSG) for each pilot site, wind data must be considered. During PMSG design stage multiple generator designs are obtained. In order to select the generator design more suitable from each pilot site several criteria are considered. Generator production is one of these criteria used to select the optimal generator design. To calculate this production wind data distribution is needed.

- Technical choices

Global characteristics from the wind can help to choose about the correct location of a wind turbine. More precisely, the wind rose and moreover the potential rose highlight where to install the machines. Because the potential rose is generally speaking very oriented (generally speaking, medium and high winds in a specific place are always blowing from only one or two directions), one can avoid bad configurations (wake of building, leeward of a hill, wake effect,…).

In complex environment, such as urban ones, wind characteristics can help choosing a technical answer to the constrains. Here, the high turbulence and low homogeneity of the flow invite to avoid a classical Horizontal Axis Wind Turbine, and to prefer a Darrieus Helicoidal machine. Because of the high level of vertical shear (there is quite “no” wind close to roof), a crosswind installation is preferred. Last, in order to reduce rotational speed (to reduce fatigue and sound), the largest diameter possible is chosen.

- Mast and anchorage dimensioning

The high wind characterization is necessary to design mast and anchorage system. This is necessary to operate the wind turbine in safe conditions.

- Noise emission and propagation

The turbulence level is a key parameter of the noise sources level. Turbulent length scales is also an important parameter because of the correlation of sources along the blades.Turbulent length scales can have also an impact on sound propagation.

For small wind turbines, the inflow noise is the dominant noise source (noise from Large turbines is predominantly generated by boundary layer noise which is less dependent on the inflow turbulence). Inflow noise is generated by ingested fluctuations on the blade surfaces and is dependent on both the Turbulence intensity and length scales. Inflow noise follows the following relationships originally formulated by Amiet[2] and then modified for wind turbine applications with a directivity function and reference to blade segment length.

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[2] R.K. Amiet, 1975. Journal of Sound and Vibration 41, 407-420. *Acoustic radiation from an airfoil in a turbulent stream*

$$SPL_{Inflow} = SPL^{H}_{Inflow} + 10\log(\frac{LFC}{1+LFC})$$

$$SPL^{H}_{Inflow} = 10\log(\frac{(l/2)L}{r^2}M^3u^2_{turb}\frac{\hat{k}^3}{(1+\hat{k}^2)^{7/3}}\bar{D}) + 181.3$$

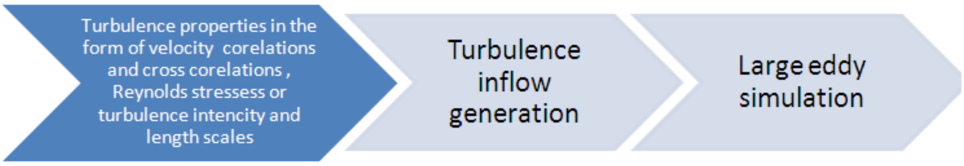
$$LFC = 10\frac{S^2MK^2}{1-M^2} : K = \frac{\pi f c}{U} : \hat{k} = 8\pi f L U/3$$

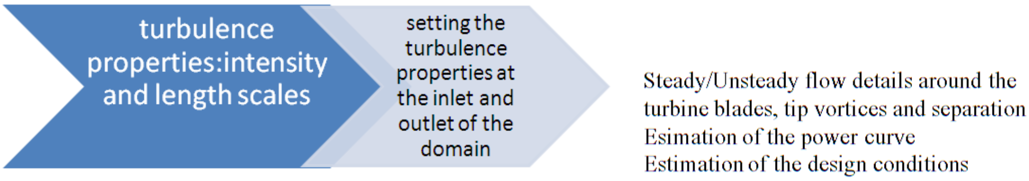
$$S^2 = (\frac{2\pi K}{1-M^2} + (1+2.4\frac{K}{1-M^2})^{-1})^{-1}$$

- Blade aerodynamics

In order to optimize the blade design, highly detailed calculations can be driven in Computational Fluid Dynamics. These techniques, such a Large Eddies Simulation, need hypothesis about the inflow characteristics: turbulence intensity, turbulence length scales, (lateral and vertical correlation lengths are also appreciated but very difficult to measure).

While the general flow details provide information about the appropriate location for the turbine installation, the turbulence properties enable accurate prediction of the power curve and performance of the wind turbines. In practice, thorough information about the flow and turbulence details is the main key to optimize the design for each demo location.





Conclusion

In this paper, we present a complete and deep modelization of wind characteristics. A present the techniques to obtain these characteristics. Last, we present the use of these parameters in all the different fields of a wind generator design (blades, electrical generator, sound, anchorage,…)