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Profile Tests to Optimize the Utilization of Wind Energy

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Abstract – We have to know the property of air movement in hub height of wind turbine on understanding that we want to utilize of wind power economically. We can calculate wind speed from near ground measurement to hub height but always have mistake in results depend on applied method. In Hungary the Hungarian Meteorological Service carried out expedition wind measurements with SODAR equipment to study wind potential of the country within a frame of a scientific competition. We analysed SODAR data from Budapest, Paks and Szeged with statistical method looking for answer to our following question: How can frequency distributions of wind speed and wind direction in different height change? Are there any differences in form of wind profiles and in wind power in different wind direction sector? How can daily course of wind speed and potential of wind energy in different height change? At the same time, we suppose that there is a so-called "inflection altitude," where the daily course of the wind speed and wind energy is random. We try to determine this altitude on the basis of tower measurements in Paks. Finally we get an example to the distribution of specific wind power according to parts of the day

power law exponent / daily course of wind speed / SODAR and tower measurements

Kivonat – Profilvizsgálatok a szél energetikai hasznosításának optimalizálásához. Ismernünk kell a légmozgás tulajdonságait a szélerőmű tengelymagasságában, amennyiben gazdaságosan szeretnénk hasznosítani a szél energiáját. Talaj közelében végzett mérésekből számítható a tengely magasságában a szél sebessége, azonban eredményeink az alkalmazott módszertől függően mindig hibával terheltek. Magyarországon az Országos Meteorológiai Szolgálat SODAR berendezéssel végzett expedíciós szélméréseket az ország szélpotenciálját felmérő kutatás keretében. Ebben a tanulmányban Budapesten, Pakson és Szegeden végzett SODAR mérések adatait statisztikai módszerekkel elemeztük a következő kérdésekre keresve a választ: Hogyan változik a szélsebesség és a szélirány gyakorisági eloszlása különböző magasságban? Van-e különbség a szélprofil alakjában különböző irányszektorokban? Hogyan változik a szélsebesség és a fajlagos szélteljesítmény napi menete különböző magasságban? Ugyanakkor feltételezzük, hogy létezik egy ún. „inflexiós magasság", ahol a szélsebesség és szélenergia napi menete véletlenszerű. A paksi toronymérések segítségével próbáltuk meghatározni ezt a magasságot. Végül bemutatunk egy példát a fajlagos szélteljesítmény napszakok szerinti eloszlásáról.

szélerő függvény kitevő / szélsebesség napi menete / SODAR és torony mérések

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1 INTRODUCTION

The National Meteorological Service has bought a SODAR (Sonic Detection and Ranging) appliance, which measures the horizontal components of wind with sound waves, to prepare a detailed study of changes in wind power vs altitude in a research aimed at measuring the solar and wind energy potential of Hungary. It is corroborated by international tests and experiences gained in Hungary that measurements by SODAR are very precise (Vogt – Thomas 1995; Seibert 1998; Baumann-Piringer 2001; Dobi et al. 2006). Several studies have been written on testing the properties of the Hellman-exponent used for a simple description of the wind-profile (Tar 2007a; Dobi et al. 2006).

By analysing the expeditionary measurements made with SODAR in Budapest, Paks and Szeged between 2003 and 2004. We were trying to find the answer to the question of how wind properties change at varying heights and which well—known wind-profile context approaches it more precisely. The properties of wind-speed and specific wind power were studied at several heights during the day on the basis of data of tower measurements in Paks, during the years 2000 and 2001 (Tar 2004, Tar 2007b).

The new measuring device can measure the properties of motion even at 20 different heights, between 30 m and 315 m with a resolution of 15 metres. One part of analyses was carried out between height of 30 metres and 120 metres in accordance with onshore wind energy utilization on the basis of data of 7 altitudes. The number of data that can be evaluated above 120 metres, as is shown by experience in Hungary, can be decreased even below 60%, which means significant statistical uncertainty. On the other hand, the full height of onshore wind turbines with rotor blades included cannot exceed 150 metres by European law, so the wind-data measured at an altitude of 120 metres provided information about wind motion characteristic of the hub height of the highest possible wind turbines which can be deployed.

The distribution of wind direction frequency was calculated on the basis of 12 30° intervals. A specific feature of the representation in *Figure*s *1*, *2*, and *3* is that it shows the distribution of wind speed with 1 m/s precision. Thus, not only the more frequent, dominant wind directions can be seen, but other ones too that is important in terms of strength and is characterized by a higher average speed. In addition, the frequency of wind direction as well as the resulting wind direction calculated by means of the average wind speeds measured by directions as show in the *figures 1-3* too.

The observations were of expeditionary nature, so the data of Budapest extends from 1st April of 2003 to 30th June, the beginning of summer. The observations in Paks were made from 1st November of 2003 to 29th February of 2004, mostly in winter, whereas the data from Szeged processed are available for 4 months from 1st June to 30th September of 2004. Wind measurements carried out between 30 m and 315 m with 1 minute frequency. The averaging period was 10 minutes.

Parts of the analyses were made with software developed by Mistaya Engineering Inc., called *Windographer 1.04*, while the others with that of Lakes Environmental *WRPLOT View 5.2.1* representing a wind rose.

2 RESULTS

2.1 Changes in wind direction and wind speed at different altitudes

Measurements made in Budapest (*Figure 1*) show that in the spring and early summer period North-Westerly winds were the most common at all altitudes in 2003. At higher and higher altitudes, the dominance of North-Western wind direction was even more pronounced marked, while closer to the ground Northern wind frequency is significant. If we account for the distribution of wind speed by direction, it can be seen that the generally dominant North-Westerly wind has the highest average speed, and through its volume, the biggest potential energy content. Detailed tests showed that wind speed is lowest at early dawn, or sunrise at all heights. During a day the highest average-speed period at height of 120 metres was typical between 5 and 10 p.m.

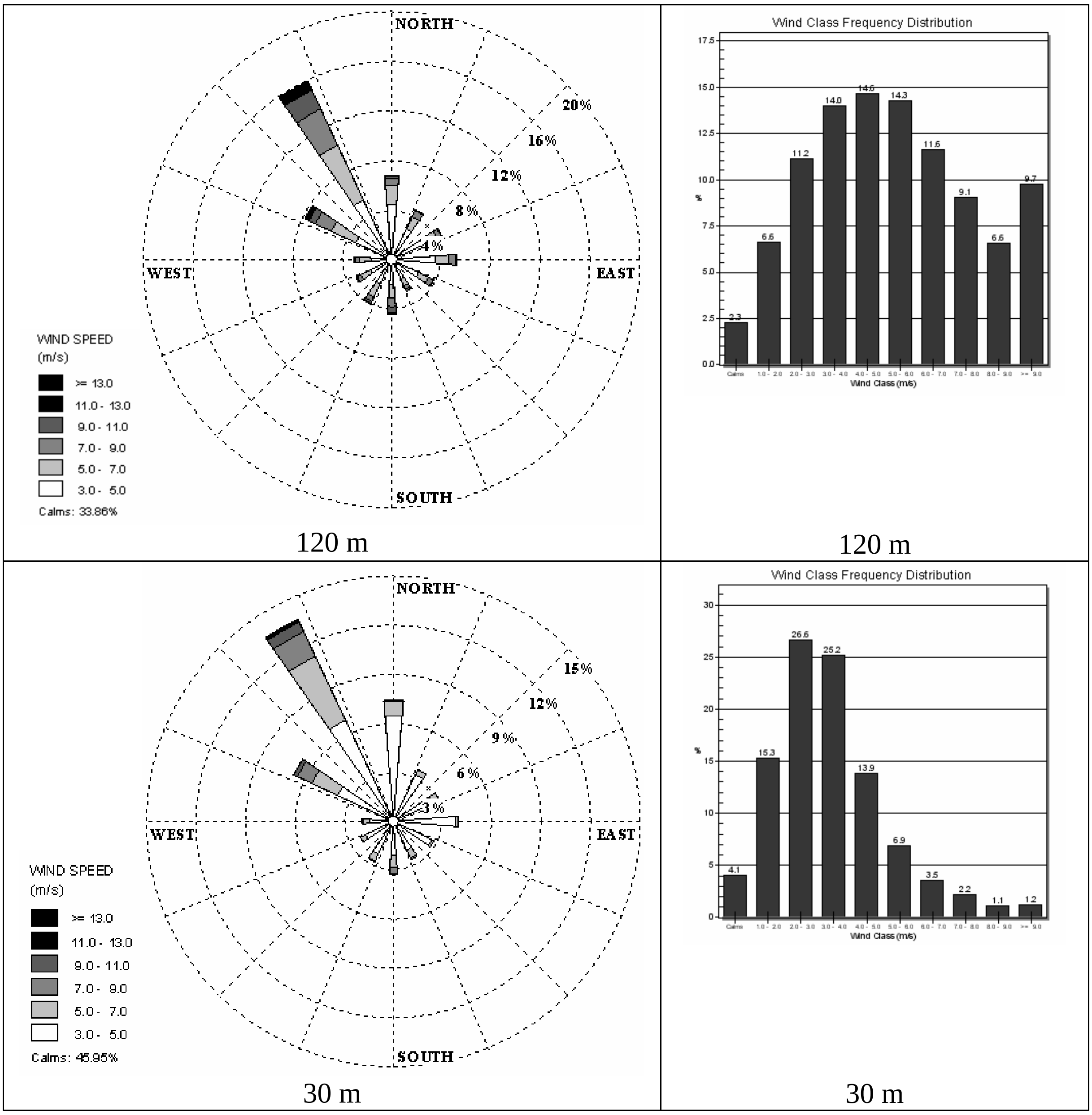


Figure 1 Relative frequency distribution of wind direction and wind speed by wind direction categories 30 m and 120 m above the surface from SODAR measurements in Budapest

The average wind speed increased at higher levels, which also leads to a change in the shape of distribution. In *Figure 1* the relative frequency distribution is shown in two heights. In Budapest, the frequency of the calm period (<3 m/s wind speed) is more than 20% even at a height of 120 m, which may reach 45% near ground level (30 m). The commonly used Weibull distribution is applied. Its scalar (c) and shape (k) parameters can be calculated in different ways at all heights. Our study shows that the shape parameter of the Weibull distribution applied for the measured data is $k=2$ and it only changes to a hundredth value up to 120 m. At the same time, scale parameter c has a speed dimension (m/s), which changes within a wide range depending on the average speed and the height (in a range of 3.9-5.96 m/s at a height of 30-120 m). As a result, the potential specific wind power of the air is almost tripled between 30-120 m (30 m: 47 W/m^2 and 120 m: 162 W/m^2).

With fluctuating wind, a wind turbine produces electricity in a well-definable wind-speed range. It reaches its nominal power at a given wind speed. It is determined by the distribution of wind speed and the technical properties of the wind turbine as a function of the time available for the wind turbine to produce electricity for a network. With the distribution of wind speed known, the value of utilized capacity factor (%) is a crucial parameter in assessing how economical a wind turbine will be and as well as in testing the feasibility of an investment. In Europe, it is 23-25%, which does not even rise above 40-45% in excellent offshore seats (IEA 2005). If there had been a VESTAS V90 1.8MW nominal capacity wind turbine with an axis height of 105 m in the examined period near the measuring site in Budapest, its capacity factor would have remained below 20% (19.2%) based on local wind measurements at an altitude of 105 m. Of course, this factor does not only depend on the technical parameters of the wind turbine, but on the wind conditions of the given year too.

The place of setting up SODAR in Budapest cannot be regarded as most optimal for a wind turbine from the aspect of energy. Although the rate of utilization is below the European average, it is not the worst in Hungary. Anyway, if we know exactly the distribution of wind-speed, we can find a type of wind turbine, optimal axis height, which exploits the local conditions best.

In *Figure* 2 it can be observed that near ground level in Paks, between 1st November of 2003 and 29th February of 2004, both North-Western-Northern and Southern-South-Eastern winds were very frequent.

This local element of the terrain is of key-importance from the aspects of wind-motion, and it can be explained with the location of the Danube Valley. The North-Western wind is dominant at an altitude of 120 m, but Southern winds, so much common elsewhere, are less frequent here.

However, the dominant character of North-Western winds is obvious based on the energy content of fair motion. Southern air motions are of primary importance mainly in the morning period, while in the afternoon and in the evening, North, North-Western winds of considerable specific wind-power are common.

Average wind-speed at an altitude of 120 m approaches 6 m/s though near ground level, the average values are around 3 m/s similarly to the one measured in Budapest.

According to measurements made mainly in the winter period, wind speed changed less during the day than in Budapest. The shape parameter of Weibull distribution (k) hardly changed ($k=2$), whereas the speed-dependent scale parameter (c) doubled (3.09 m/s 30 m, while 6.66 m/s at an altitude of 120 m). Accordingly, specific wind power at 30 m above ground level increased from 24 W/m^2 to ten times higher at 120 m, to 224 W/m^2.

The place of measurement in Paks seems a more favourable location in terms of available wind force compared to the one in Budapest, as the energy content of the wind exceeded 220 W/m^2 at an altitude of 120 m. Vestas V90 wind turbine with an axis height of 105 m, and with nominal power of 1,8 MW would have reached 25% capacity factor under similar wind condition. North of Paks, in Kulcs is an operating Enercon E-40 wind turbine with nominal power of 600 kW since 2001. According to experiences between 2002 and 2006 the yearly capacity factor has not reach higher than 25%, but the axis level is only 67 m (Stelczer, 2007).

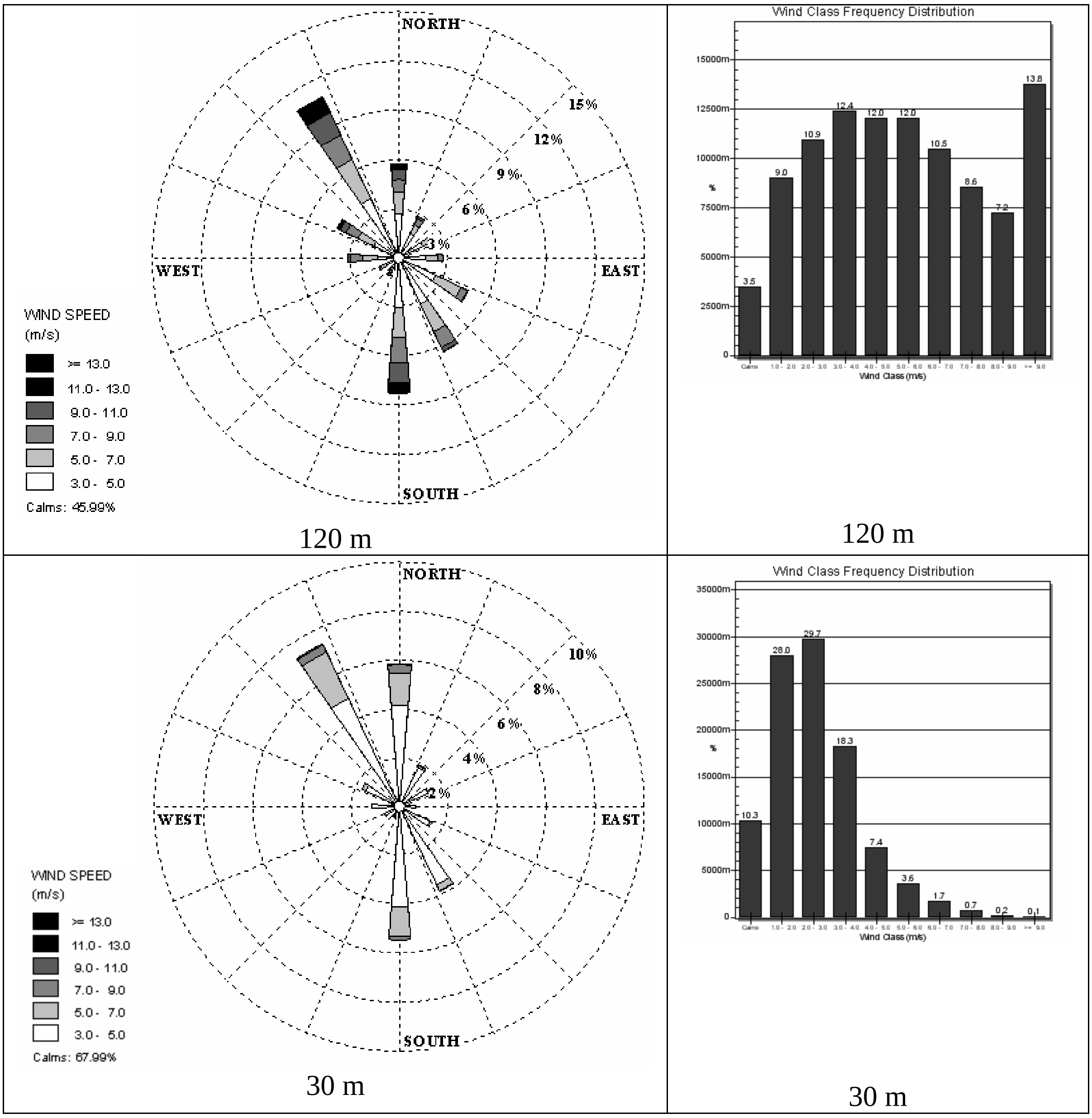


Figure 2. Relative frequency distribution of wind direction and wind speed by wind direction categories between 30 m and 120 m above the surface from SODAR measurements in Paks

The data measured between 1st June and 30th September of 2004 with SODAR at the airport of Szeged is available to analyse. The North-western winds seem to be dominant on the basis of wind direction frequency as is shown in *Figure 3*. As the height increases the number of southern directions decrease, while Northern, North-Eastern winds are more frequent, though Southern directions have strong wind speed at an altitude of 120 m. The parameters of Weibull distribution in Szeged between 30 - 120 meters are between 2.1 - 2.2, while the scale parameter (c) 30 m - 3.77, at 120 m – 6.09.

The average wind speed in Szeged at 120 m hardly exceeds 5 m/s, which means that the energy content of the summer months in 2004 at this altitude was lower than the values measured in Paks (140-160 W/m^2 at altitudes 105 and 120 m, though they did not differ significantly from the data measured in Budapest. It is common knowledge that the summer period is less windy in Hungary than winter or spring, which explains why Szeged seems unfavourable place in terms of a wind supply in the examined period for industrial-size wind turbines producing electricity for the energy network.

Taking into account the data of the measurements in the 4 month period, a Vestas V90 with 105 m hub heights with 90 m of rotor diameter and 1.8 MW nominal power could have reached around 20% utility rate in Szeged.

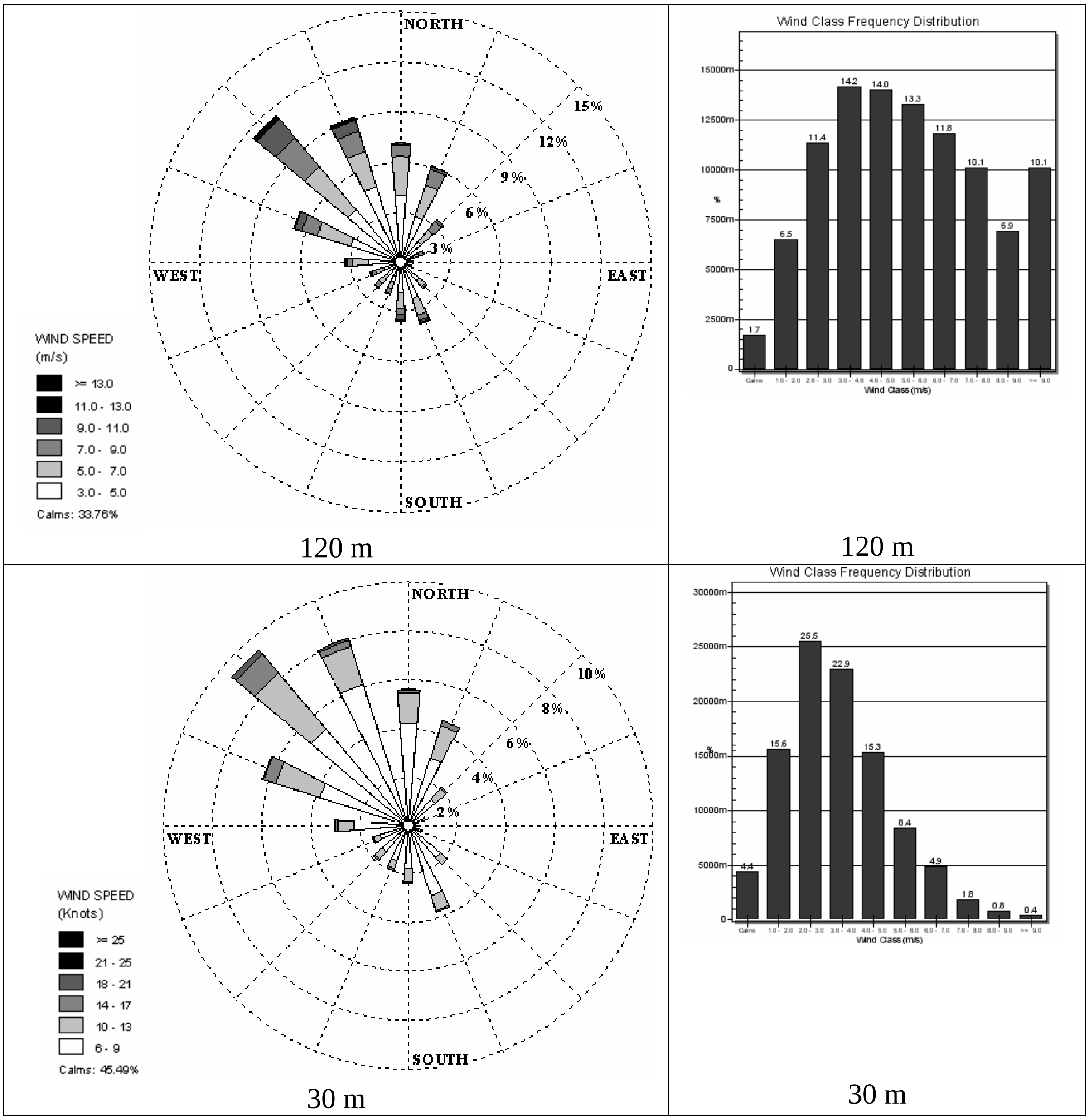


Figure 3 Relative frequency distribution of wind direction and wind speed by wind direction categories between 30 m and 120 m above the surface from SODAR measurements in Szeged

2.2 Average and normalized wind profiles

Changes in wind speed at different altitudes can be described with well-known wind-profile contexts: with logarithmic relation used in meteorology,

$$u(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \qquad (1)$$

(where u_* is friction velocity, $\kappa=0.4$ is Karman's constant, z_0 is roughness height) or in engineers' work with a simpler exponent variant,

$$\frac{u_2}{u_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \tag{2}$$

(where u_1 is wind speed (m/s) in z_1 reference height, u_2 is wind speed in sought z_2 height, and α is Hellmann's exponent).

Theoretical logarithmic wind profile (1) context can be easily used according to tests of planetary border-layers above 100 m near the ground, and at higher altitudes at 925-850 hPa altitude in almost neutral unstable balance situations, that is mainly found during the day. The fault-rate of assessment is highest near ground level, in the case of inversion, rather unstable conditions, especially at night.

Owing to the simplicity of the context (2) it is also used in the case of wind measurements aimed wind energy for the extrapolation of wind speeds for the height of the wind turbine. However, based on data from meteorological towers and wind measurements of wind energy, the value α can be made more precise according to surface friction. Radics (2004) says that the values of the exponent are 0.14 over a flat water surface, 0.2 over rough, hilly surface, and 0.28 over settlements. Though she emphasizes that the exponent α depends on wind speed (at higher wind speed its value decreases) beside the roughness of the surface and from temperature layers of the air too.

The value of the exponent has a wide range not only depending on the roughness of the surface but also as the resultant of several atmospheric factors (Tar 2007a; Dobi et al. 2006). All scenes of measurements found determinate daily course of a power law exponent, which reflects seasonal differences.

The shape of average wind profiles at the three locations is the resultant of local effects. We examined with which theoretical relationships the wind profiles defined from the SODAR measurements can be approached more precisely. *Figure 4* shows how the average wind speed calculated for the complete period of measurement depends on a height between 30 and 120 m. Quite strangely, the values of Szeged and Budapest parallel each other up to 60 m, while from this height those of Paks and Szeged, and between 55 and 60 m the averages are almost equal, about 4.2 m/s.

According to correlation indices it is the logarithmic function in Budapest, while in the other two stations the exponent one that suit the best in this layer.

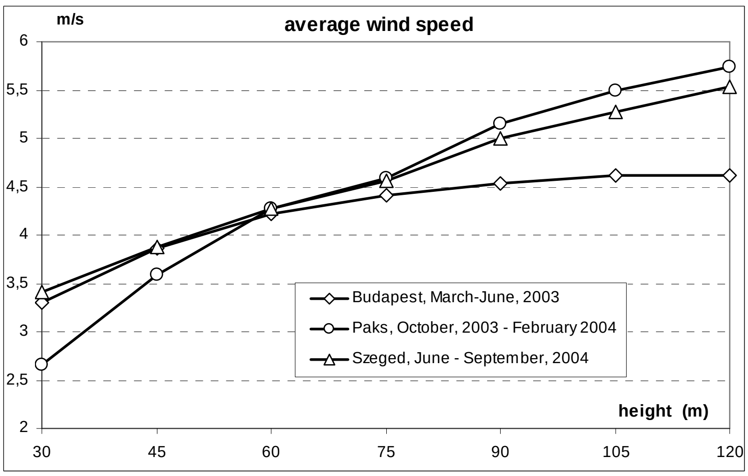
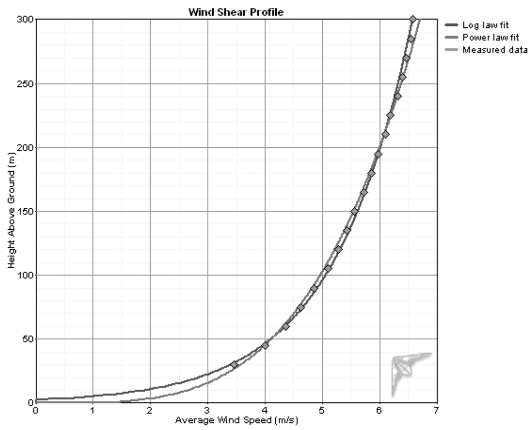


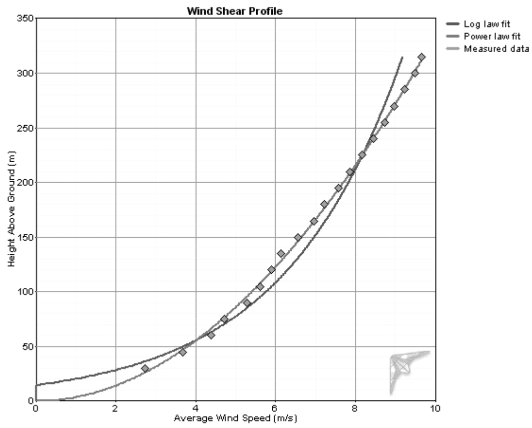
Figure 4. Average wind speeds at different heights for the whole measurement periods

When accounting for all the data available for up to 315 m, it can be pointed out that over 60 m the logarithmic context is excellent in Budapest, while in Paks was unfavourable in concept (*Figure 5*). Changes in wind speed are best described by the exponent context basically at all heights, but especially above 120 m in Paks. We found a marked breakage point in the shape of the wind profile in Szeged. There we judged the exponent formula more precise up to 75 m near the ground, while between 90-315 m the logarithmic description with a 15 m range.

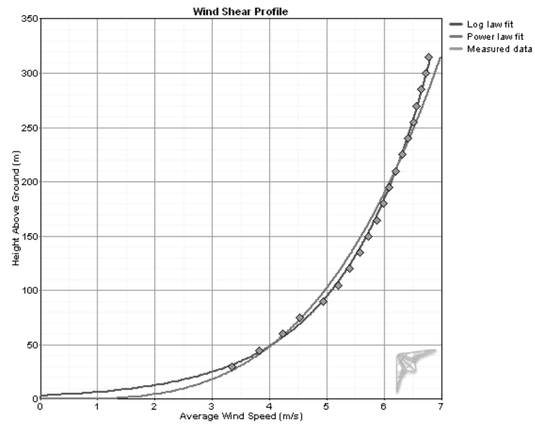
From another point of view we produced normalized profiles in the most frequent dominant wind-directions (Mellinghoff et al. 2000). When normalizing, we accounted for wind motion stronger than 4 m/s, which is of key importance in terms of energy production.



Budapest



Paks



Szeged

Figure 5 Average wind profile in Budapest, Paks and in Szeged and its fit with log law and power law function

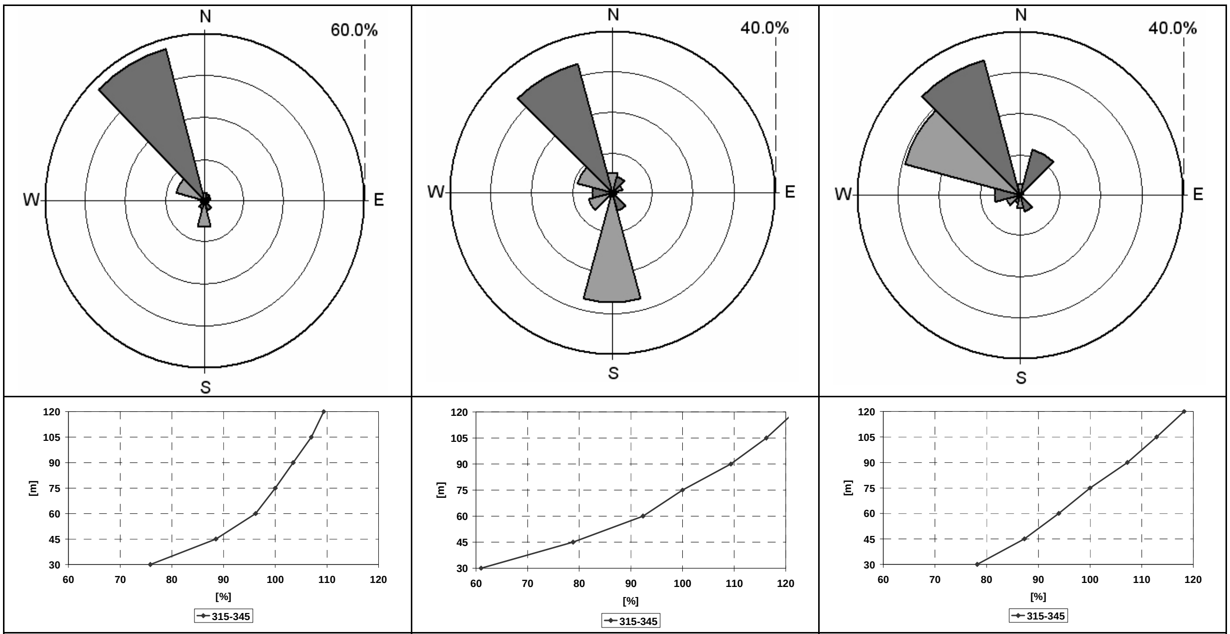
Through this condition we managed to decrease the range of our data, whereby smoother profiles could be produced. Normalization was carried out with the wind speed of the 75 m height, so the relative profile (*Figure 6*) depending on wind direction was defined from this base point.

Introducing the wind speed value virtually emphasized the defining character of north-western 315-345° wind direction sector in all locations. This means that we can compare different locations with identical wind directions. The typical wind direction in Paks is (180°) Southern, while in Szeged sector 275-315°.

It can be seen in *Figure 6* that the speed of north-western wind is 25% lower at 30 m above ground level than at 75, but it is only 10% higher at 120 m. There is an inflection point in the relative profile at about 60 m, and the wind speed per unit height above it hardly changes.

The gradient of wind speed was the highest in Paks, as near-surface wind was even 40% weaker, while at the seventh level it was more than 20% bigger. The speed difference of the two levels was almost twice as high as in Budapest.

On the whole, the experience gained in Szeged was positive compared to Budapest, though as effective as that obtained in Paks. The difference in speed between 30-120 m was almost 40%. The decrease in wind speed near ground level was more moderate, which may be related to the kind of terrain found on the plain.



Budapest | Paks | Szeged

Figure 6. Frequency distribution of wind direction, and normalised wind profile in prevailing wind direction, where average wind speed is higher than 4 m/s, in Budapest, Paks, and in Szeged

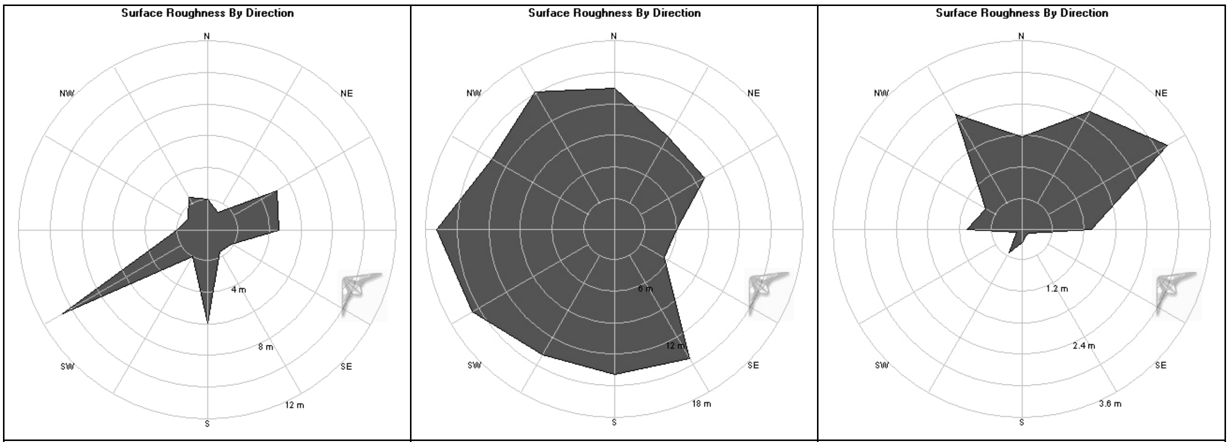
Szeged can owe its more favourable evaluation in terms of commercial utilization of wind energy to the fact that the dominant wind direction is westerly, and that winds higher than 4 m/s arrive frequently from sector 285-315°. This local characteristic feature would moderate energy quantity, which would be exhausted by the wind turbine when turning into the direction of the wind.

2.3 Factors influencing the shape of the wind profile

There is general agreement in the literature that apart from the characteristics of the surface (the relief, the cover of the surface, roughness and artificial obstacle) the shape of the wind profile above ground level is regulated by atmospheric factors too. So, it is affected by large area weather phenomena, stability of the atmosphere, its temperature structure as well as the distribution of humidity. During the research, SODAR was only set up on a plain, whereby we could disregard the complex effect of the relief. This made the roughness of the surface a significant factor.

The roughness height z_0 in the logarithmic wind profile means the theoretical height where, wind speed becomes zero. If we know the typical roughness height value of an area, the speed of wind can be defined for other heights with a certain wind profile.

If the wind profile is well-known, roughness height z_0 can even be calculated for wind direction sectors, or in the Hellman context (2) the value of the exponent. This means that SODAR measurements provide detailed information on the close vicinity of the measuring place. Ideally, wind measurements of energetic nature should take place in an environment complying with the practice of synoptic stations, in a completely open flat, short-grassed area with a roughness height area of z_0=0.03 m. Very low z_0 value should be calculated in all directions. On Figure 7 shows calculated z_0 value from SODAR measured wind profile in synoptical station of Hungarian Meteorological Service in Budapest, Paks and Szeged. It can be seen in *Figure 7* that none of the locations seem ideal from all points of view.



Budapest	Paks	Szeged

Figure 7. Effect of roughness by wind directions in Budapest, Paks and in Szeged

In the surroundings of the Budapest (Pestszentlőrinc) measuring station we found effects of buildings, or a higher roughness element in north-eastern north-western direction (Figure 7). The main observatory of Hungarian Meteorological Service is suburb surroundings of SE part of Budapest. The location is mostly flat, but observatory is on a small hill, so higher than surroundings area. In Paks, the effects of local elements of roughness could be measured virtually from all directions in the period of data collection. This location proved very rough by all categorizations of roughness. This meteorological station locates close to forest belt of the nuclear power plant in Paks, so this forest has an influence on wind measurements. In Szeged the meteorological station located in western side of city nears the airport. We can observe clearly that the north-north eastern sector is characterized by high roughness, while from southern directions the measuring point is completely open. In the north-eastern direction we detected the effects of the industrial and suburban area of Szeged approx. 500m from measuring station.

Our former statements were also corroborated by the values of α exponent in the exponent context defined by wind direction sectors (2), which is shown numerically by *Table 1*.

By this table in the case of Szeged the average is α=0.2, in Budapest it is nearly 0.3, while in Paks it is α=0.4-0.5. If we consider that wind from the north-western (330°) is dominant, then Budapest and Szeged are very similar, α=0.26 , while in Paks it is α=0.52. The latter values reveal good correlation with our results calculated from tower measurements in Paks (Tar 2004, Tar 2007b).

From the aspect of practical use it is worth considering that if the wind reaches our wind turbine from a surface of low roughness in the dominant wind direction, we can produce electricity with a smaller turbine as wind speed is stronger near the surface. In an area of higher roughness, however, we had better choose a bigger wind turbine.

Table 1. Average power law exponent by wind directions in Budapest, Paks and in Szeged

Medium value of wind direction sector (°)	Budapest	Paks	Szeged
0	0.260	0.504	0.244
30	0.235	0.447	0.268
60	0.324	0.427	0.287
90	0.321	0.355	0.238
120	0.252	0.339	0.159
150	0.245	0.501	0.152
180	0.342	0.495	0.168
210	0.256	0.513	0.193
240	0.434	0.539	0.155
270	0.256	0.561	0.222
300	0.239	0.512	0.204
330	0.267	0.526	0.269
α exponent value average	0.29	0.48	0.21

2.4 Determining the „inflection altitude”

It is interesting both from an energy and a practical perspective that the wind speed changes in various layers of the atmosphere according to a different daily course. Over ragged surfaces, up to a supposed altitude of 60-80 m (Radics 2004), wind speed increases at around sunrise, and reaches its maximum by early afternoon. By contrast, at higher altitudes, it shows the opposite course, i.e. it reaches its minimum level around noon. Naturally, the same daily courses can also be observed in both the potential wind energy and in terms of energy utilised as electricity. According to our preliminary studies (Tar in press), the full-day and half-day periods of the daily courses were only realistic in the two layers in a negligible percentage of the cases. At the same time, we suppose that at the boundary of the two layers there is a so-called “inflection height,” where the daily course of the wind speed and wind energy is random. At this height, wind energy may be considered as constant over the entire day, meaning that the operation of a wind power plant would require fewer tasks from the perspective of the electric control systems. The amount of wind energy that can be produced here, is likely to be less than at higher heights.

The basis for the elaboration of the method used for determining the inflection height and the average energy content of the wind was the wind speed data measured every ten minutes at height of 20 m, 50 m and 120 m on the meteorological tower of Paks in 2001. *Figure 8* shows the average daily course, calculated for the entire year, at the three heights.

The average speeds for the entire year were 2.8, 4.0 and 5.9 m/s, while the standard deviation was a 0.47, 0.25 and 0.49 m/s, respectively. The fluctuation of the average annual course at 50 m, therefore, is half of the value measured at the other two heights, which suggests that the inflection height should be sought around here. Further reinforcing this hypothesis are the values of the variance ratio (standard deviation / average), which are 0.169, 0.063 and 0.082, respectively.

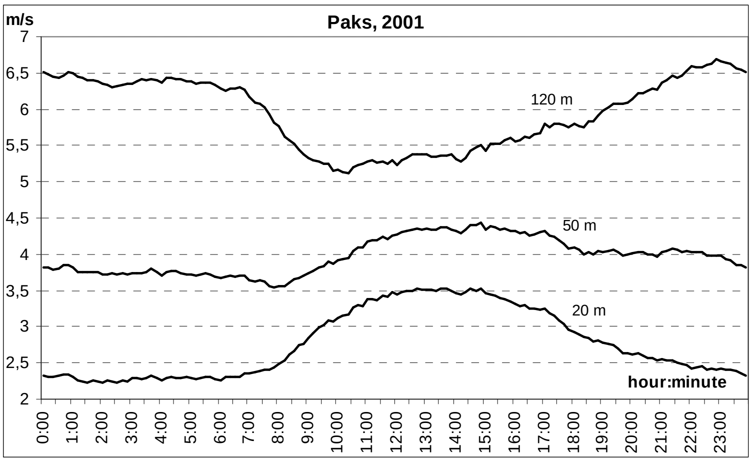


Figure 8. The daily course of the annual average of wind speed data measured every 10 minutes at heights of 20, 50 and 120 m at Paks

The wind speeds measured at every 10 minutes at the three altitudes can be used to determine the current values of the α index of (2), the so-called Hellmann's law, taking various altitudes as the starting level. The average of these will yield the daily average course of the power law exponents, which is shown in *Figure 9*. It is α(h1, h2) on the figure that means the annual average of the current values of the power law exponent calculated from height h1 to height h2 (where h1<h2). The daily averages are, in all three cases, 0.45, the standard deviations are 0.17, while the variance ratios are 0.37. The average values are higher than the values found in the relevant literature. It can also be seen in the figure (*Figure 9*) that the values of α(20,120) can be regarded as the average of the other two. Therefore, this power law exponent will be calculated with first.

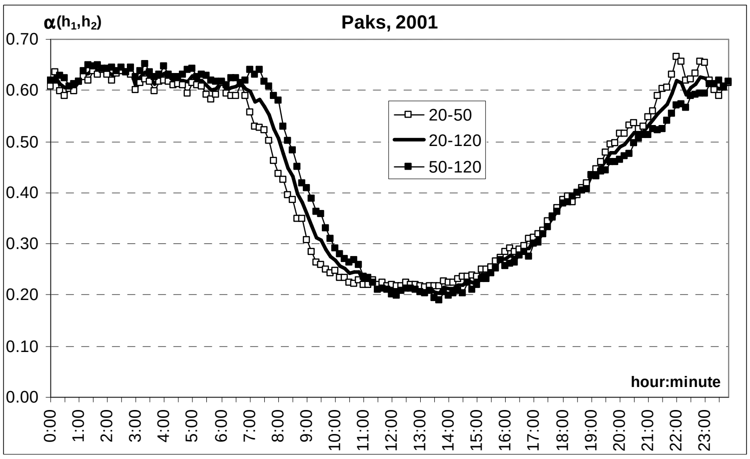


Figure 9. The daily course of the annual average of the Hellman indexes calculated every 10 minutes at Paks

First of all, the error in the estimate with the values of the average daily course of α(20,120) were determined. From the current wind speeds at 20 m, we calculated the speeds at 50 m and 120 m, and with the measured values in hand, we determined the relative error of the estimates in%, and then took the average of these values. The daily course of the average values is shown in *Figure 10*. It can be seen that, as expected, the error of the estimate is generally higher in case of speeds at 120 m altitude, especially in the daytime period. The value of the daily average relative error was 4.8% at 50 m and 5.7% at 120 m.

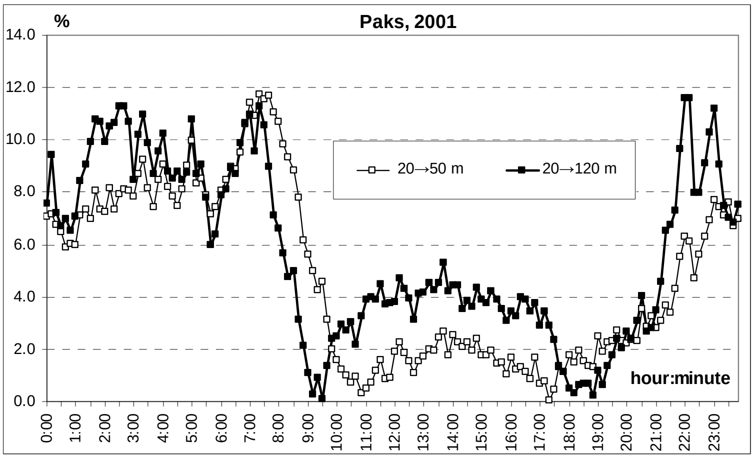


Figure 10. The daily course of the relative error of the estimate with α(20,120) the average power law exponent (20 m → 50m ; 20 m →120 m)

Next, using the 10-minute average values of α(20,120), we calculated the estimated values of the wind speeds and wind speeds raised to the third power for every 10 minutes from the wind speed data measured at 20 m.

The average value of the latter for each point in time is proportionate to the value of the wind power, which means we thus also received the daily course of the average wind power.

Figure 11 shows the annual average wind speed calculated from the estimated values of the wind speed, as well as the standard deviation and the variance ratio. The power law function laid on the average values shows a fairly good correspondence (the correlation index is 0.9952) with a power law exponent (which is also the value of the Hellmann index in this case) of 0.34. The values of the standard deviation and the variance ratio take their minimum values at 50 m, which suggests that the inflection height should also be around this point.

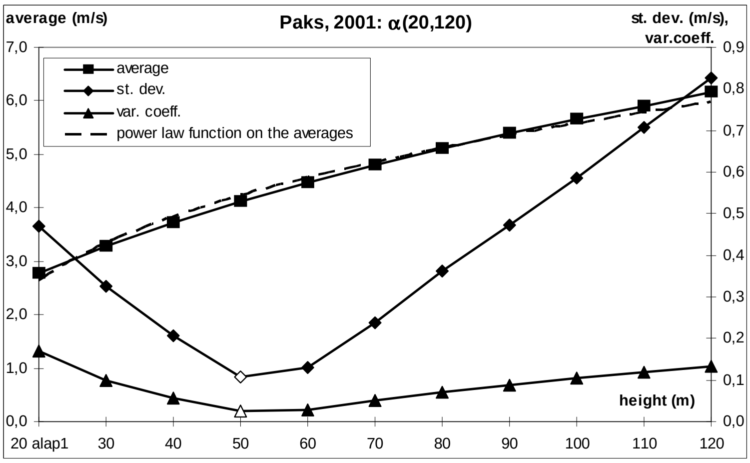


Figure 11. The annual average wind speed and the variance ratio at different altitudes, calculated from 20 m with the α(20,120) average power law exponent

Figure 12 provides further basic statistics on the estimated values. The fact that these are fairly close at a height of 50-60 m also reinforces our earlier hypothesis.

In order to confirm this we carried out a time-series analysis of the average daily courses of the wind speed values raised to the third power at various altitudes: we set a trigonometric polynomial consisting of two waves, and examined the reality of the amplitudes of these.

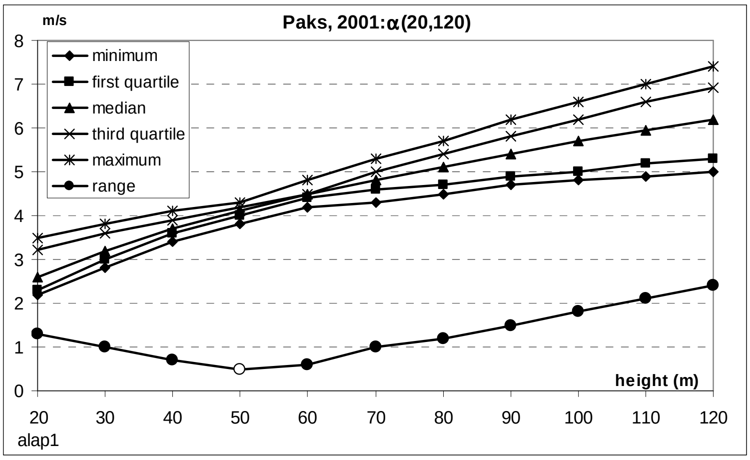


Figure 12. Further basic statistics at various altitudes, calculated from 20 m with the α(20,120) average power law exponent

That level was considered as the inflection height, where the period of either wave (24 or 12 hours) was random, and therefore, its amplitude not significantly different from 0. This can be determined with the A_m/E ratio of the individual amplitudes (A_m, m=1,2) and the expectancy (E, the expected value of the amplitudes) defined by the formula

$$E = s_n \sqrt{\frac{\pi}{N}} \qquad (3)$$

If the A_m/E ratio is big enough, then there is a low probability (p) for the period to be a result of the random arrangement of the data, which means that it can be regarded as realistic from a statistical point of view. Generally a value of $A_m/E>2$ can be regarded as acceptable (p=0.05), but in case of the period analysis of weather data, a given wave is also regarded as realistic in case of $A_m/E>1.5$ (p=0.17) values (Koppány 1978). In *Figure 13,* the dependence of the A_1/E and A_2/E ratios on height was depicted. It is seen that the first, 24-hour wave can be regarded as realistic at all altitudes on a 0.05 significance level; however, at 40 m, the A_1/E proportion is 3, decreasing to the critical value belonging to the 0.01 significance level. At 50 m, the second wave of 12-hour period becomes random. This means that the 12-hour period from this point on will not characterise the daily course of the average wind speed values raised to the third power. We therefore believe that the inflection height is around 40 m.

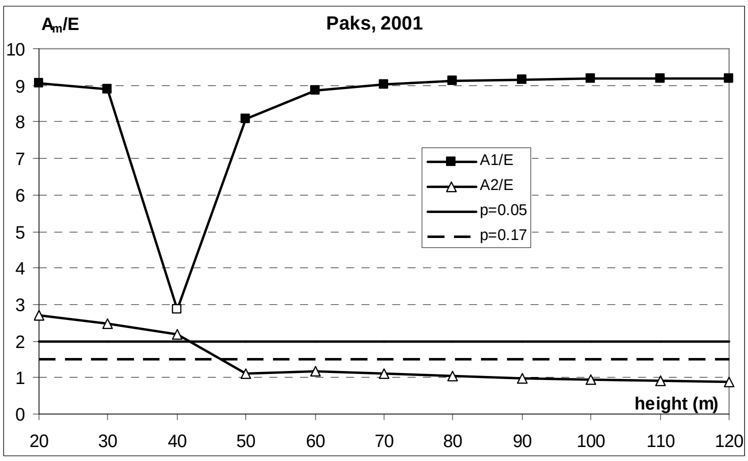


Figure 13. Dependence of the A_1/E and A_2/E ratios on height in Paks

This is also reinforced by *Figure 14*, where the averages calculated from the measured (20 m) or estimated (30, 40 and 50 m) values, as well as their approximations by 1 or 2 waves were plotted at the 20, 30, 40 and 50 m altitudes. It can be seen that at 50 m, the two approximation curves run together, which means that taking the second wave into consideration does not alter the correctness of the approximation. The same can also be experienced at greater heights.

From the comparison of *Figure*s *8* and *14* we can see that the daily course of the estimated values of the measured wind speed values and the wind speeds raised to the third power are different, which partly results from the raising to the third power, but primarily from the error of the estimation. We can conclude, therefore, that the inflection height in the period, year 2001, was around 40 to 50 m, and that the daily course has its maximum value below and its minimum value above this height at around 1 p.m.

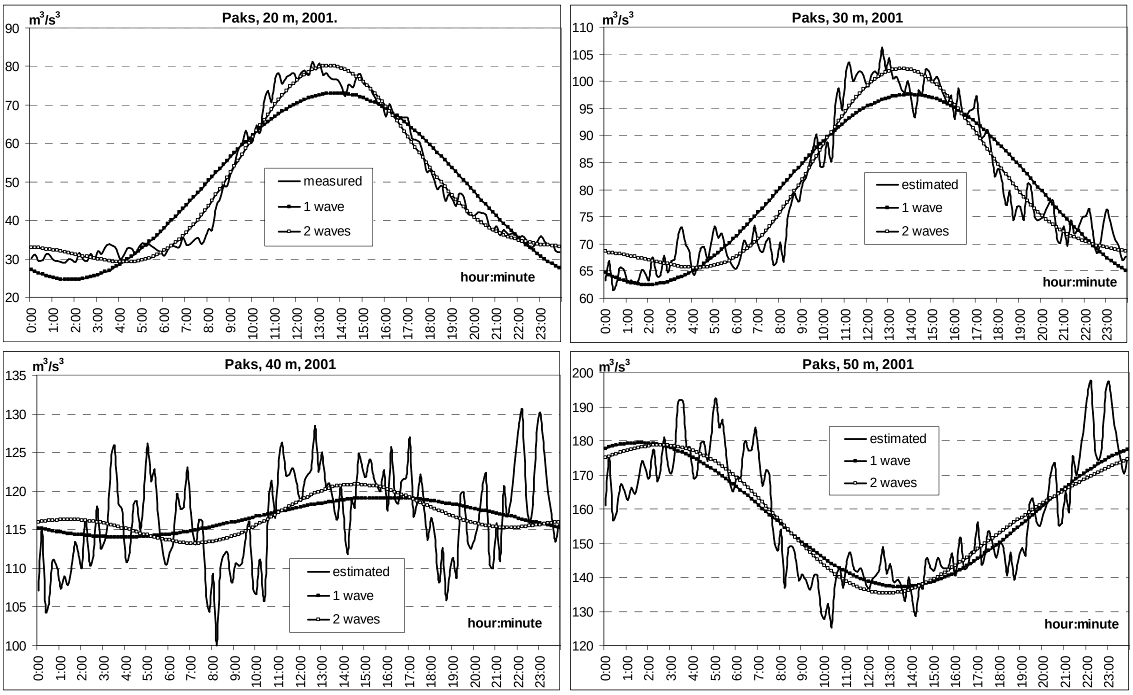


Figure 14. The daily course of the measured or estimated average wind speeds raised to the third power, and their approximation by a trigonometric polynomial consisting of one and two waves

2.5 The distribution of specific wind power according to parts of the day

The specific wind power falling on a single day of a longer time period can be defined as follows: the area under the curve of the approximating function laid on the daily average course of wind speed values raised to the third power. In our case, this function is a trigonometric polynomial consisting of two waves, which has a primitive function, and so the area under the curve can be determined by a definite integral.

In *Table 2* we provide the average specific wind power calculated for the daytime (9 a.m. to 7 p.m.) and the night-time (7 p.m. to 9 a.m.) periods, expressed as a percentage of the total daily average specific wind power.

According to the table, the potential daytime wind power is only higher or equal with the night-time values up to an height of 30 m. The latter is already twice of the former at an height of 60-70 m, and more than 3.5 times the former at 120 m.

Table 2. The average specific wind power calculated for daytime and night-time periods in percentage of the total daily average specific wind power in 2001 in Paks

	Daytime	Night-time
	(%)	
20 m	58.2	41.8
30 m	49.1	50.9
40 m	42.7	57.3
50 m	37.9	62.1
60 m	34.1	65.9
70 m	31.0	69.0
80 m	28.5	71.5
90 m	26.5	73.5
100 m	24.7	75.3
110 m	23.1	76.9
120 m	21.8	78.2

3 CONCLUSION

From the analysis of the research data by SODAR carried out in Budapest, Paks and Szeged, we can make the following statements:

- From the point of view of energy utilisation, it is the north-western winds that have more significant energy content. In case of Paks and Szeged, southern winds are also favourable.
- The wind speed shows characteristic daily courses at different heights. The minimum levels are measured at sunrise and early morning at all height levels. The maximum daytime wind-speed is measured near ground level. The maximum of the daily course above 60-90 m was typical in the late afternoon and in the evening hours. This indicates that even though the construction of increasingly higher hub height wind turbines is believed necessary in Hungary, these wind turbines will generate most electricity not in the period of highest energy demand, this will constitute a system control problem.
- In the measuring points without effects of the terrain, the logarithmic relationship for the description of the average wind profile proved to be better in Budapest and Szeged. The high-gradient wind profile in Paks could be better described with the use of the power law exponent formula. We examined the daily course of the average power law exponent in this formula, and found that in Paks and Szeged, a fairly definite daily course, depending on the stability of the atmosphere, could be observed, which also reflects the seasonal differences. With the average wind profile known, we determined the z_0 roughness altitude, as well as the α exponent of the power law exponent relationship, which proved the direct effect of the roughness elements in the vicinity on the shape of the wind profile.

From the data of the tower measurements in Paks, the following could be determined:

- In Paks, on the basis of the average of 2001, the inflection height, i.e. the height where the wind speed has no daily course, is located around 40-50 m. The daily course around 1 p.m. has its maximum below this altitude and its minimum above it.
- The potential daytime wind power is only higher or equal with the night-time values up to an altitude of 30 m. The potential wind power is already twice as high at night at an altitude of 60-70 m, and more than 3.5 times at 120 m than the corresponding daytime values.

We also intend to carry out further measurements aimed at determining the inflection height and the daily courses of wind energy at other locations, with the use of the SODAR equipment. According to *Figure 4*, the average speeds between 50 and 60 m are more or less the same at all three locations studied; therefore, we expect results similar to that published here. For this reason, the authors propose the reconsideration the concepts of utilisation of wind energy in Hungary.

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