St. ISTVÁN UNIVERSITY

DEVELOPMENT OF ENERGETIC-PURPOSE WIND MEASUREMENT SYSTEM

Theses of doctoral (PhD) dissertation

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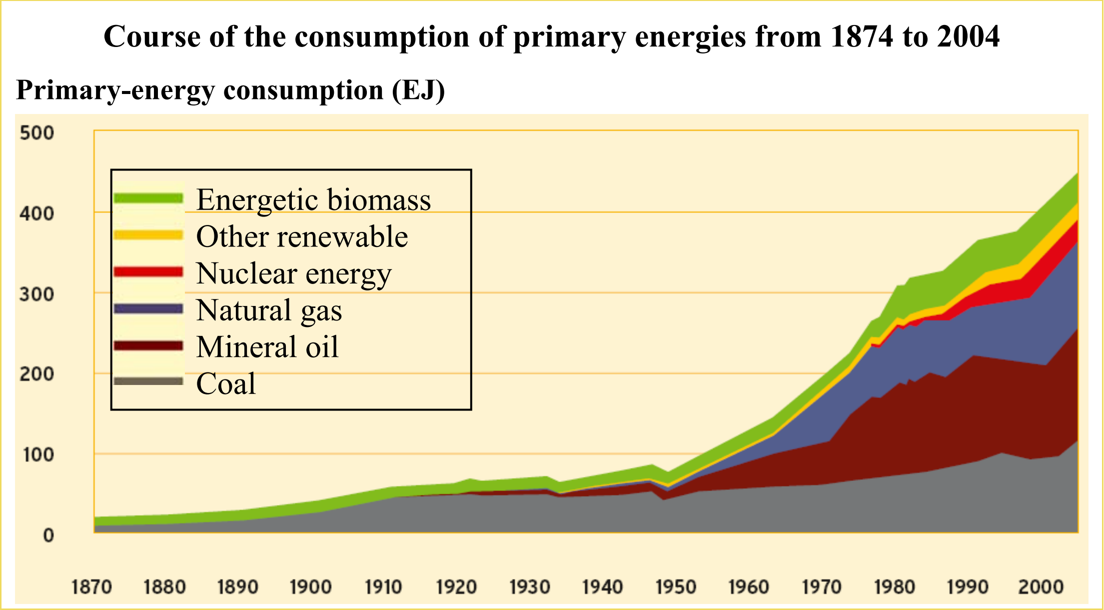
1 Introduction

1.1 Importance of the theme

The energy management and the sustainable energy supply in connection with it is a better and better central problem of the economy of the 21st century. There have been on international researches and negotiations concerning a sustainable development, for decades. The purpose of the wide-range co-operation and activity is that the developing world should create a tolerant connection with the surrounding natural environment, at the same time sustaining the economical growing, and improving the human living conditions.

‘The energy supply is sustainable only if it provides a wide-range and durable availability of the used energy resources and, at the same time, limits the concerning negative effects.’ *(UN Conference on Environment and Development, June 1992)*

Since the beginning of the industrialization the energy consumption of the mankind has been increasing at much higher rate than that of the population. While the population of the world has increased up to its quadruple (6.3 milliard), the energy consumption and, together with it, the use of fossil energy agents (coal, mineral oil and natural gas) – up to its sixty-fold value; it was 450 Exa-joule (1 EJ = 10^{18} J). (Fig. 1.1)



Course of the consumption of primary energies from 1874 to 2004

Primary-energy consumption (EJ)

Fig. 1.1 *Course of the consumption of primary energies from 1874 to 2004 (Source: Statistic data IEA, 2005)*

Wind is one of the natural energy resources and its role has changed several times during the history of the mankind.

The kinetic energy of the wind transformed into mechanical energy can be used, amongst others, for driving electric generators. In the course of the technical history, as to its construction, designs of different kinds were developed; however, wind generators with horizontal axis of rotation have become the most common up to now. The reason is the significantly higher volume in its electric-energy production.

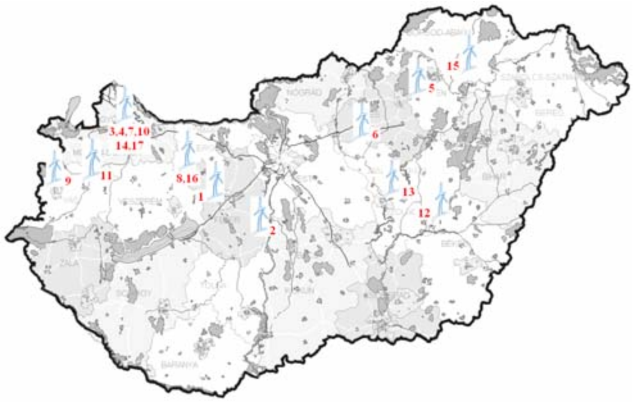


Fig. 1.2 *Location of the wind-power plants and wind-power parks erected in Hungary at the end of 2006 (source: author's mapping)*

Table 1.1 Wind-generator capacity of Hungary at the end of 2006 (in kW)

Location		Type	Electric power	Height	Number of units	Year of erection
			(kW)	(m)		
1	**Inota**	N29	250	40	1	2000
2	**Kulcs**	E40	600	65	1	2001
3	**Mosonszolnok**	E40	600	65	2	2002
4	**Mosonmagyaróvár**	E40	600	65	2	2003
5	**Bükkaranyos**	V25	225	29	1	2005
6	**Erk**	E48	800	76	1	2005
7	**Újrónafő**	E48	800	76	1	2005
8	**Szápár**	V90	1800	80	1	2005
9	**Vép**	E40	600	65	1	2005
10	**Mosonmagyaróvár**	E70	2000	113	5	2005
11	**Ostffyasszonyfa**	E40	600	78	1	2006
12	**Mezőtúr**	FL MD 77	1500	100	1	2006
13	**Törökszentmiklós**	FL MD 77	1500	100	1	2006
14	**Mosonmagyaróvár**	V90	2000	105	5	2006
15	**Felsőzsolca**	V90	1800	105	1	2006
16	**Csetény**	V90	2000	105	2	2006
17	**Levél**	G90	2000	100	12	2006
			Electric power (kW)		**Number of units**	
	Total		**60,875**		**39**	

(source: author's tabulated chart)

1.2 Objectives

During the past five years a significant transformation process of the energy system started in Hungary. One of the segments is focused on the wind energy as a renewable resource. At the beginning of my research in 2002 a total wind-generator capacity of only 2-MW nominal power was available in Hungary. Today the nominal electric power capacity of the wind-power plants already exceeds the value of 60 MW. The short-term purpose is a capacity of 330 MW to be established until 2010.

When preparing this dissertation, I envisaged as an objective that it shall be connected definitely to the erection process of wind-power plants in Hungary.

The objectives in connection with the dissertation, established during this work:

- Construction of the first energetic wind chart of Hungary, based on the results of the energetic-purpose wind measurements at more than 30 basis points, and using the long-term database of the Országos Meteorológiai Szolgálat (*National Meteorological Service*), in the frame of the work in a consortium
- Recording the special conditions of the expected erection sites in Hungary, taking the operating heights of the generators, the local varying of the turbulences, the special wind profiles, and the applicability of the available pieces of software into consideration
- Determining the accuracy of the calculated and the factual wind-measurement data with the help of the wind tunnel made especially for this purpose
- Investigation of the measurement systems used for the energetic-purpose wind mapping, taking the suitability for use into consideration

1.3 Questions to be solved

1) Review and selection of the bibliography sources on the theme
2) Construction of a wind tunnel and the measurement system suitable for the data processing for the testing of anemometers
3) Control testing of the sensor instruments before and after the one-year energetic wind measurements
4) With the help of the carried-out wind measurements, determining the wind-energy properties of the actual site in the way that it shall provide information for the users as well – particularly as to the values of Hellmann's exponent and the parameter k of Weibull's function – and the interpretation of all these in the domestic conditions
5) Making the wind chart based on the meteorological data base, and mapped by projection accurate
6) Comparison of the measurement systems used actually for energetic wind tests
7) Estimation of the energy yield and the analysis of the reliability of forecasts of electric energy production with wind-power plants
8) Adaptation of the energetic wind measurement and planning to the main geographical properties of Hungary

2 Material and method

2.1 The calibration system developed in the course of the research

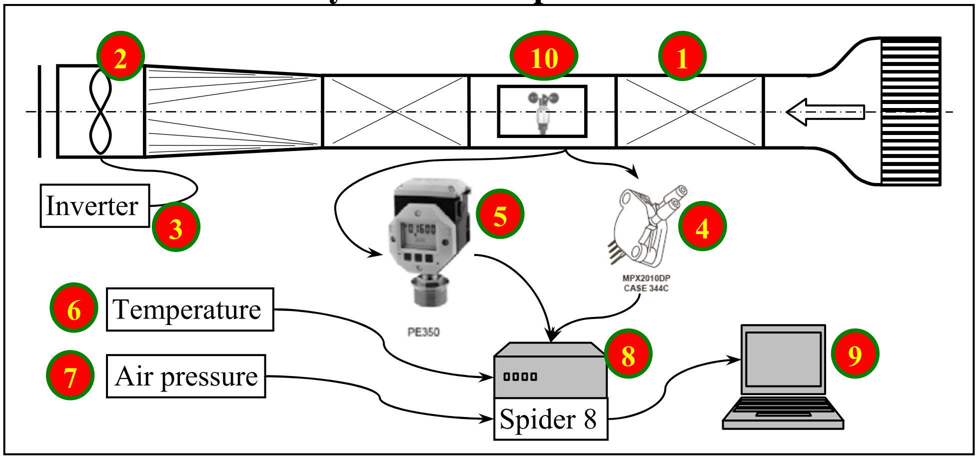


Fig. 2.1 *Measuring circuit diagram*
(source: author's design)

Elements of the measuring circuit:

1) Wind tunnel
2) Fan (Helois HQ 630)
3) Frequency inverter
4) Differential pressure manometer (Motorolla MPX 2010)
5) Differential pressure manometer (HBM Digibar II. PE350)
6) Air-thermometer
7) Air pressure manometer
8) Measuring data logger
9) Portable PC (HP OmniBook XE$_3$)
10) Anemometer (Thies Compact)
    Anemometer (Thies Classic)
    Anemometer (Thies First Class)

2.1.1 Construction of the wind tunnel

The construction was designed in the Dept. of Fluid Mechanics, Institute of Environmental Systems of 'St. István University.

The wind tunnel is of suction system; a constant depression is maintained in its measuring space during the measurement. The length of the tunnel is 6 m wich is divided into six sections. The cross-section of the measuring space is a regular square of 500 × 500 mm into which the object to be tested (in this case, the cup anemometer) can be placed through the access hole in the wall of the tunnel.

A differential pressure manometer was inserted in the measuring space; its function was to deliver the voltage values proportional to the pressure values in the tunnel. The proportional voltage values are suitable for storing them in a computer, and using them as reference values after reconverting during the testing of anemometers. The access hole in the side wall of the measuring space provides the insertion of the objects to be tested, and the terminals of the cable connected to the data logger unit.

The Prandtl pipe of the differential pressure manometer is placed before the anemometer by 350 mm so eddies formed by the cups do not influence the measured data.

2.1.2 Calibration of the wind tunnel

Certificating calibration by this wind tunnel cannot be carried out since the permission of the OMH (*National Office of Measures*) has been lacking as yet. The method of the calibration of the wind tunnel is that the wind speed is measured at several points of the cross-section of the tunnel, in parallel with the flow direction, and the flow pattern is induced by constructing a diagram with the gained values. For calibration of the anemometers, an even wind-velocity profile is suitable which must be constant about the instrument. Taking this into consideration, an inset piece had to be substituted for the measuring section of the wind tunnel; I designed the changes required for carrying out the measurement on this inset piece. The measurement principle was based on that, at measuring points of sufficient number, I could construct a representative pattern of the flow in the tunnel. For this purpose I vertically bored eight holes through the top wall of the tunnel, at the distance of 62.5 mm from each other. Through the bore-hole, I inserted a cup-head Prandtl pipe vertically downwards and I fixed it in eight different depth positions with also 62.5-mm distances.

The measurements were carried out at the rotary speeds 500, 1000 and 1500 rpm which were adjusted a frequency converter used for the fan speed control.

2.1.3 Calibration of the anemometers

For calibration, at first I used the differential pressure manometer Motorolla MPX 2010 as a reference sensor. The data logger was the instrument type Spider 8 of Hottinger Baldwin Messtechnik GmbH.

The measuring range of the data logger type Spider 8 is capable of dividing the received signal into 25,000 digits. The set measuring range was 100 mV. The output signal of the differential pressure manometer MPX 2010 was 25 mV. The Spider could divide this into the fourth of its measuring range e.g. a part of 6250 digits. The measurement domain of the differential pressure manometer is between 0 and 100 kPa (10,000 Pa); since the maximum output signal (25 mV) corresponds to the value 10,000 Pa, 1 digit = 10,000 / 6250 = 1.6 Pa. This value is the so-called ‘digit error’ of the transmitter MPX 2010 which arises with the 0-1 junction e.g. the error of the differential pressure manometer is 100 % when measuring 1.6 Pa in the applied measuring circuit. With an increase of the measured signal, the ratio of the measurement error decreases e.g. the measuring accuracy increases. In this actual case, the error of the measurement with the differential pressure manometer decreases to such a degree that the test results will be comparable and interpretable. Because I did not considered the resolution of the reference signal to be satisfactory, I inserted another differential pressure manometer in the measurement circuit (type Digibar II. PE350). With the help of the measurement system developed in this way, the anemometers can be calibrated with an accuracy of triple order.

Fig. 2.2 *Wind tunnel in the laboratory of FME SZIU*
(designer: F. Szlivka – B. Balló)
(source: author's photograph)

With the help of the developed measurement system, I controlled the operation of the cup anemometers in 108 tests. In the course of this, I recorded 30,000 measurement data from a measuring sensor. The large-number sampling provided the induction of the later conclusions.

2.2 Energetic-purpose anemometric measurements in the practice

The measuring methods and the used instruments used in the practice of the energetic-purpose wind measurements are presented in this chapter.

2.2.1 Versions of the on-tower measurements

The energetic-purpose wind measurements belonging to this category can be classified into 3 main groups as follows –

1) *Informative anemometric measurements*
   Measuring stations of the meteorological service or systems recording data averaged for a longer time established about the erection site
2) *Wind measurements with the purpose of erection*
   Measuring systems erected exactly on the construction site of wind-power plant to be established, taking the micro-relief conditions and unevenness properties of the surface
3) *Checking measurements* (in the areas of wind-power parks)
   They may be the bases of the earlier used erection-purpose anemometric measurements and which later are maintained as checking units

It has to be determined already during the preparation process of the wind energetic projects, with full knowledge of the measurement spot, which measurement is reasonable to be applied.

To determine this, it has to be known the following facts –

- the wind-speed and wind-direction values concerning the actual site or its ambience in the data base of the Országos Meteorológiai Szolgálat (OMSZ – *National Meteorological Service*),
- the local orographic conditions (the effect of the expected friction factor),
- the natural or artificial elements of the environments affecting the flowing properties of the wind (such as the character and degree of the plant cover; the co-ordinates of the artificial ground objects and/or the settlements, and their geometric dimensions,
- the economical size of the project.

Depending on the purpose of use e.g. the character of the measurement, there are different measurement systems known. The collection of the instruments and the auxiliary equipment is based first of all on technical and economical aspects.

On the basis of the measurement data of OMSZ (*NMS*), an informative representation can be formed about the characteristic wind conditions of the site at the height of 10 to 12 m. With the help of this, knowing the relief and the environmental conditions, and using an average altitudinal correction (Hellmann's factor), the local capabilities can be estimated.

If the measurement spot cannot be characterized definitely because of the orographic and environmental conditions, a preliminary, so-called informative measurement is advisable. In the best case, the wind measurement with the purpose of erection is advisable to be carried out in the expected site of the erection of the wind generator from the first instant of the start of the measurements.

2.2.2 Measurement data with the system SODAR

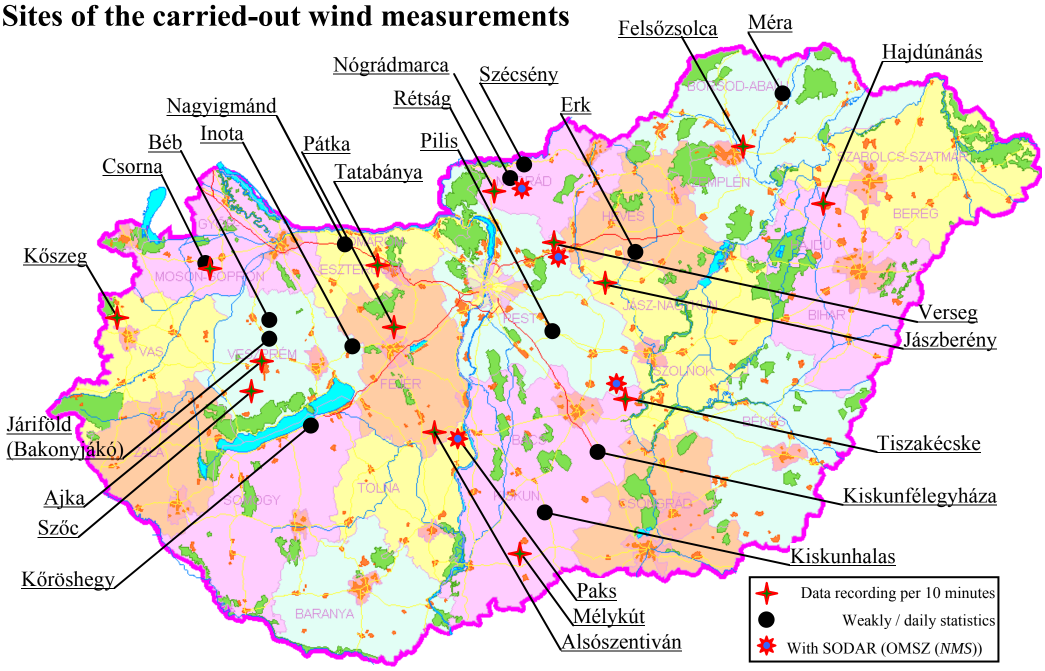
The wind-velocity data gained with the SODAR are received in the preset units (mph; km/h or m/s). The direction values delivered by the instrument are defined in degrees. The sampling takes place in by 3-second periods and the instrument forms normal averages of 10 minutes. When interpreting the collected data, the software shows the speed and the direction of the wind with small wind vanes of different sizes and directions. From this, it can be seen well how the wind direction and velocity changes vertically as a function of the height in the actual 10-minute measuring period. The processing of the numerical data can be completed with the help of both the Excel and the software WindPRO used frequently in the field of the wind energy utilization.

With this measurement method, data of the wind velocities and directions can be gained at even 20 measuring heights. Practically, it facilitates the construction of the real actual wind profile. As to the averaging of the measured data in every 10 minutes, it makes the scanning of the variation of the vertical wind profile in time.

2.3 Processing of the data base of the energetic wind measurements

During the research period (btw. 2002 and 2007), I carried out and managed energetic-purpose measurements in 26 sites (in the frame of a research consortium NKFP (*Nat. R+D Pro.*)). (Fig. 2.3)

During this, I could know the measurement systems used frequently in the practice of the wind-energy utilization, and the evaluation mode of the collected data. The calculation of the expectable energy production is a manifold and complicated task. The design process of the wind-power parks, the spacing of generators and the determination of the expected production data of each wind-power generator, with an acceptable accuracy, demands great care. Due to the sampling per second in each of the actual sites, 31,536,000 data lines were processed. The following chapter includes the way of the data base processing.



Sites of the carried-out wind measurements

***Fig. 2.3** Energetic wind measurements carried out in the research period (source: author's mapping)*

2.3.1 Measurement-data processing with the software WindPRO 2.5

The software is based on a developed measuring system; it is already capable of directly evaluating the measured data. The data base to be utilized is usually generated by averaging the measured data in every 10 minutes. As a minimum, it contains the average values and deviations of the wind velocities at two heights, and the average value and deviation of the wind directions at one of these heights. It is capable of processing measurement data at even more height levels as well as processing the maximum and minimum values detected of the single sensors. The detailed data base facilitates the exact calculation of the energy yield when planning wind-power parks.

3 Results

My test results gained in the research period are shown in this chapter, which I have used for establishing new scientific results.

Here the following issues are analysed in detail:

- evaluation of the measuring results gained when calibrating the wind tunnel
- test results of cup anemometers
- investigation of the learnt energetic-purpose anemometric systems
- experiences of the evaluation of the measurement data
- determination of the expectable energy production

3.1 Evaluation of the results of the wind-tunnel measurements

In the course of the evaluation of the measured data, the deviation of the air-flow velocities from the average value was investigated. The agreed acceptable error limit in the hydromechanics is ± 4 %. This deviation shows at which degree the wind speed (or air-flow velocity) values vary from the average value of the air-flow velocity characteristic of the actual fan rotary speed. If the values remain in the range between the above ± 4-% limits, the air flow (velocity space) is considered as homogenous. After the analysis of the measurement data, it can be established that the 50-mm thick border layer of the cross section is not suitable for reliable measurements but the test velocities remain between the limits of ± 4 % in the inner zone of the wind tunnel.

The maximum tip-circle diameter of the tested anemometers in my research was 240 mm and the diameter of the cups – 80 mm as a maximum. This means that the equal air-flow velocity with maximum ± 4-% error limits must be provided in a range with dimensions of 240-mm width and 80-mm height.

It is important to be marked that the rotary mid-plane of the rotor of the anemometer should be set to the measuring level at the distance of 156.25 mm from the top wall of the wind tunnel. This is indicated by the cross-sectional flow pattern recorded by the 8 × 8 measuring matrix applied in the test tunnel.

In sum, it can be stated that the wind tunnel is suitable for fluid-mechanical testing of cup anemometers if the operation of the anemometer can be controlled in the three-dimensional space, completely fulfilling all hydro-mechanical requirements.

On the basis of the results from the control investigation, I have found that the wind tunnel is suitable for the fluid-mechanical testing of cup-type anemometers.

3.2 Evaluation of the calibration results of the anemometers

In the energetic wind measurements, I used the cup-type anemometer as measuring sensor to determine the wind velocities. The calibration characteristic curve of this instrument is to be measured and recorded before the practical use for the sake of the exact evaluation of the data.

The control tests of different anemometers made by Thies were carried out, altogether in 120 cases. The static measurement was effected with ten constant velocity values in every case.

The measuring time at a velocity value was $T = 10\ min$.

The sampling time was set to $t = 0.5\ s$.

The measurements were carried out in the laboratory of the Department of Hydro-mechanics of SZIE-GÉK (FME SZIU).

During the measurements I always recorded the ambient conditions.

Comparing the data measured by the anemometer with those measured the differential pressure manometer chosen as the control instrument, it can be established that that the results fit well on a straight line; the relationship between the signal of the anemometer and the wind velocity values is linear. The instrument runs properly and it is in accordance with the manufacturer's characteristic relationship e.g. that the wind-speed value is directly proportional to the path length covered during the revolutions. However, it can also be established that the anemometer measures lower values all the measurement range over than the reference instrument i.e. the given relationship does not define exactly the relationship between the covered path length and the velocity.

This can be well demonstrated by the calculation of the absolute and the relative error. For determining a more accurate relationship, I approached the relation between the two values with a higher-order function. In the course of this process I established, using the relationship –

$$v_{corrected} = v_{measured} + \left|0.001 v_{measured}^2 - 0.0593 v_{measured} - 0.1985\right| \qquad (3.1)$$

that the corrected values approaches the values measured with the reference instrument by a 99.56-% accuracy and both the absolute and the relative error approaches zero:

$$-0.046\ m/s < absolute\ error < 0.013\ m/s$$

$$-1.005\ \% < relative\ error < 0.74\ \%$$

When determining the relationship, I aimed at finding a power regression function with the possibly minimum exponent but keeping, at the same time, the possible closest approach to the real values.

3.3 Comparison of the measuring systems

3.3.1 The change in the parameter 'k' of Weibull's function in Hungary

The first step in the processing of measurement data to be recorded by the wind-speed measuring systems is the classifying of data. The data classes are constructed in column (bar) diagrams. For an easier determining of the expectable energy production, the changes in the wind speeds, the variations of data can be estimated with the help of distribution functions.

For describing the distribution of the wind velocity, mostly the Weibull distribution function is used of which form for the field of the wind-energy utilization is as follows:

$$f(v)=\frac{k}{v_{average}}\left(\frac{v}{v_{average}}\right)^{k-1} e^{-\left(\frac{v}{v_{average}}\right)^{k}} \qquad (\%) \qquad (3.2)$$

where v = wind velocity (m/s)
$v_{average}$ = average wind velocity (m/s)
k = shape factor

It can be seen that only one parameter characterizing the measurement site is in the function – a special value: the factor *k*.

With increasing the height, the value of *k* increases as well. Accordingly, when comparing different sites to each other, it is important that the values of *k* should be referred to the same height.

The data in Table 3.1 are the average values featuring the individual measurement sites and they were gained as the weighted averages of the values by the 12 compass points at the height of 60 m. The measurement was carried out by sampling second by second, and averaging data in every 10 minutes. The colour marking refers the relief character of the measurement site. Brown marks the hill-country areas while green – the plane areas of Hungary.

Table 3.1 Course of Weibull's factor in Hungary

Location	**Weibull's *k* factor**
Ajka	1.948
Alsószentiván	2.330
Bánk	1.627
Bogyoszló	1.928
Felsőzsolca	1.705
Hajdúnánás	2.025
Jászberény	1.740
Kartal	1.948
Kőszeg	1.895
Mélykút	2.267
Nagyigmánd-2005	2.109
Nagyigmánd-2006	2.241
Pátka	2.025
Szőc	1.871
Tatabánya	1.845
Tiszakécske	2.023

It can be seen from the gained results that the value of Weibull's factor k exceeds 2.0 in the plain country of Hungary in the most cases while it is much below 2.0 in the hill-country areas.

3.3.2 Change in the altitude exponent in Hungary

Today in the energetic wind measurement practice, the typical way is the velocity-sensor technique with cup anemometers mounted on measuring pylons in the most cases.

One of the features of these measurements is that the measured data are gained from definite height levels according to the mounting positions of the anemometers. It results from this that direct information can be gained about the wind conditions only in a narrow range of the operating height of the actual wind generator.

With the purpose of describing the full range, we have to apply a theoretical model. Amongst several other functions, in the utilization practice of wind energy, the so-called power function with Hellmann's exponent is the most frequent:

$$\frac{v}{v_{ref}} = \left(\frac{h}{h_{ref}}\right)^{\alpha} \qquad (3.3)$$

where

v = the wind velocity value (m/s) to be established at the height h (m)

v_{ref} = the known wind velocity value (m/s) at the reference height h_{ref} (m)

Several environmental parameters, according to the measurement site, influence the value of the Hellmann factor. These are the relief (the orographic properties), the altitude or height, the different meteorological properties (temperature, humidity, barometric pressure), the cover degree and character of the land surface. Accordingly, the exact determination of the value of this factor is possible only by measurements on the spot.

There have been several investigations on determining the average value of Hellmann's factor related to Hungary. Amongst these, the studies by Gábor TÓTH and Károly TARR are to be enhanced.

Gábor TÓTH dealt first of all the daily course of the variation of the factor alpha in an actual measurement site. As to Károly TARR, he determined the values alpha according to the compass points in the same place.

A fundamental difference between these investigations and my study is that I could obtain data bases of almost 40 measuring spots in Hungary (included 26 own measurements) and not only that of a single place; inclusive of the data bases of 15 measurement sites where I carried out highly accurate measurements based on sampling second by second.

In Table 3.2, I listed the average values of the altitude correction factor in the sites where I used the frequent sampling method. I marked with green colour the data obtained in the planes of Hungary while the brown colour marks the hill-country character of the sites in a similar manner of that in Table 3.1.

Knowing the sites, it can be established from the data that, contrarily to the Weibull factor *k*, the Hellmann factor depends at a higher degree on the micro-orographic elements which refer to the cover character and degree of the land area.

On the basis of data gained and related to the height of 60 m, the value of Hellmann's factor for the larger regions of Hungary alters in the range $0.15 \leq \alpha \leq 0.40$.

An adequate determination of the altitude correction is essential for the calculation of the energy production.

Table 3.2 Course of Hellmann's factor in Hungary

Location	Hellmann's factor
Ajka	0.2241
Alsószentiván	0.3998
Bánk	0.3991
Bogyoszló	0.3615
Felsőzsolca	0.2015
Hajdúnánás	0.2776
Jászberény	0.2876
Kartal	0.2541
Kőszeg	0.2336
Mélykút	0.2938
Nagyigmánd	0.2269
Pátka	0.2560
Szőc	0.2941
Tatabánya	0.1692
Tiszakécske	0.2946

3.3.3 Measurement systems operating by different measuring principles

In this measurement series, I compared the measured data of the measurement system equipped with anemometers with the measurement data of the instrument type SODAR. The goal of the comparison was to assess the applicability of the SODAR for energetic-purpose wind measurements.

There some differences in the operating of the two systems. The SODAR takes samples in every 3 seconds and averages them for 10 minutes; the Ammonit takes samples in every second and averages them for 10 minutes.

The basic difference is between their sensing modes; the SODAR (SOnic Detection Ranging) is such a measuring device which measures the direction and the velocity of the wind on the basis of the emission of acoustic waves and their reflection and receiving in the instrument.

During the measurement a sound radiator (speaker) group with 64 units emits a sound-wave beam at first in the vertical direction which is reflected from the micro-eddies continuously existing in the atmosphere. After the sound radiators change over to the ‘receiver or microphone’ function and detect returning sound waves deformed by a phase shift. The following sound-waves are emitted with a 25º declination in the direction north while the last – with a 25º declination in the direction east.

The anemometers are optoelectronic instruments measuring impulse signals in the direct ratio of the revolution number and the factual values of the path length or the covered distance are deduced from these data. The value obtained in this way relating to the time produces the velocity. The measuring of the wind direction is effected by a wind vane; it provides an infinitely variable detection with a potentiometer output.

The source of the data base used in my work was provided by the SODAR device operated by the national meteorological service. During the investigation, the measuring domain was set to the range 30 to 315 m and the vertical resolution value was 15 m. The time between the actual emissions and the detections was 3-4 seconds. As to the received data, they were recorded after averaging by the instrument.

Taking also the forecast requirements into consideration, choosing the best way, I could compare the data with the help of the daily average values.

According to the calculated absolute and relative errors, I can be stated that –

- in terms of the longer-term data lines, the SODAR usually measures lower values than that of the anemometer e.g. the SODAR works with a negative error
- the error is between 0.6 and 1.0 m/s, according to the comparative measurements carried out in several sites in the country
- in the case of the analysis of shorter-term data bases, the average deviation may decrease to even 0.2 m/s but the standard deviation of the error will significantly decrease

In addition to the areas mentioned above, I could evaluate the measuring system SODAR with the help of data lines from the surrounding regions of Szécsény, Paks and Szeged. Summarizing these analyses, my conclusions are as follows:

The measurement system SODAR –

- is suitable first of all for the estimation of the expectable energy yield,
- provides an informative data base of making a decision whether it is worth carrying out on-tower measurements requiring a significant investment because
- it is capable of quickly mapping the site (recoding the real vertical wind profile by directions, based on data at 20 altitude levels).

Its other advantages are –

- the relatively quick erection and
- the mobility of the system.

Disadvantages of the systems amongst others are that –

- the effects of the definitive atmospheric properties (such as the variation of the temperature, barometric pressure, humidity, density of air etc.) upon the system are not known;
- likewise, the effects of the natural environment are not known (e.g. sound reflection from a flying object – which is a negligible event as to its frequency but it belongs to this list);
- due to the measuring mode, the noise sensitivity of the instrument is significant (that is why, reasonably, the lowest measuring level is to be set at 40 to 45 m);
- the mode of the calibration is indefinite or it is based e.g. just on measurement data bases of cup anemometers; accordingly,
- it has to be controlled in a difficult way (it should be compared with single reference cup anemometers at each measuring heights).

Its other disadvantages are that –

- it requires a continuous mains supply and
- the risk of endamaging the system is significant (it can be placed only in a fenced and guarded area);
- due to these two features, its planting in a site is limited.

During the comparison of the two systems, I did not carry out wind-profile analyses since I did not consider the data of two altitude levels comparable with the data of twenty measurement heights.

3.4 Testing of the measurement results

There were 2 sites amongst my measurement spots where wind generators were erected – a wind-power generator type Enercon E-48 with a rated capacity of 800 kW, and a tower height of 76 m, at Erk (Fig 3.1) and another plant type Vestas V90 with a rated power of 1.8 MW, and a tower height of 105 m, at Felsőzsolca.

Fig. 3.1 *Wind generator at village Erk (Enercon E-48, 800 kW, 76 m)*
(source: author's shot)

I compared the expected results calculated from the data of the energetic-purpose wind measurement data with the factual production yields. I established that the energetic-purpose win measurements provide an acceptable accuracy for the forecast of the expectable results; the factual energy yield proved this.

The measurement is always carried out before the erection so, of course, the calculated values are different from the later measured results since the inherent power capacity of the wind varies during the years. The value of the deviation may be 10% as well or even 20 % in an extreme case. However, for a whole year the real deviation is maximum 10 %; the value of 20 % can be characteristic in short periods of a year.

I could manage to effect a comparison of the data base gained from the energetic-purpose wind measurement carried out ‘close to’ an already running wind power plant (at the distance of 30 km) with the production yield recorded simultaneously – only in the region about Mosonszolnok.

On the basis of the measurements carried out, erection of new wind-power plants is intended in other 5 sites: Ostffyasszonyfa, Ajka, Székesfehérvár, Csorna, and Komárom.

4 New scientific results

1) The value of the wind-path length characterizing the cup anemometers used in the investigations and analyses, when calibrating the sensors, must be defined with using a relationship of the second degree in the case of static or dynamic loads – contrarily to the linear relationship given by the manufacturer. Instead of the usually used relationship –

$$v(t) = m \bullet impulses + c$$

for energetic-purpose measurements, using the relationship –

$$v_k(t) = v + |m_{k1} \bullet v^2 + m_{k2} \bullet v + c|$$

the relative error can be reduced to the value $< 1\ \%$ in comparison with the value $5\ \% < relative\ error < 20\ \%$.
The calibration according the original relationship may result in a deviation of $relative\ error > 15\ \%$ when calculating the expectable energy production.

2) At the beginning and the end of the measurements exceeding the period of $T \geq 2$ *years*, a significant difference can be shown in the error curves measured and recorded in wind-tunnel tests. The Hungarian as well as the international standards has to be corrected; the calibration of the cup anemometers should be required after the measurement periods as well, in order to reduce and correct their measuring error.

3) The use of the unified altitude-correction factor for construction of a wind-energy chart of Hungary is not adequate. During mapping, it is necessary to determine the values of the correction factor in function of altitude for at least the main geographic units of country separately, and in a distribution according to the wind directions.
For the geographic country units of Hungary, the characteristic value of the altitude-correction factor can be interpreted at a unified height above the ground level – reasonably, at $h \geq 40\ m$.
For lack of measurements, in estimating calculations, taking the orographic conditions of Hungary into consideration, the values –

$\alpha \geq 0.30$ for hill-country areas
$\alpha \leq 0.30$ for plane-country areas

can be applied at the height of $h \simeq 40\ m$ above the ground level.

4) According to the detailed energetic-purpose wind measurements, the values of the parameter k in Weibull's function used for characterizing the distribution of the wind velocity –

$$f(v)=\frac{k}{v_{average}}\left(\frac{v}{v_{average}}\right)^{k-1} e^{-\left(\frac{v}{v_{average}}\right)^{k}} \quad (\%)$$

referred to the geographic regions of Hungary are as follows:

$k \leq 2$ for hill-country areas
$k \geq 2$ for plane-country areas

The value of the factor k varies with the directions and the altitudes as well. For lack of measurements, in calculation of estimation, taking the orographic conditions of Hungary into consideration, the values –

$k = 1.95$ for hill-country areas
$k = 2.10$ for plane-country areas

can be applied at the height of $h \cong 60\ m$ above the ground level.

5) The data base of the SODAR device, in the energetic calculations for a shorter period, cannot be used since the relative error exceeds the value of 10 % in the range $3\ m/s \leq v_{SODAR} \leq 8\ m/s$.
The SODAR is advantageous mainly in preliminary assessment of the wind conditions of an actual site for making a decision on the reason of a more expensive detailed measurement. Its application is especially reasonable in the case of the altitude levels $45\ m \leq h \leq 150\ m$, and of significant turbulent flows as well as the local topographic and friction elements highly modifying the flowing. At the measuring heights $h > 150\ m$, the ratio of the fade-out occasionally exceeds 20 % so, in these cases, the data base cannot be considered as representative.

6) According to the analysis of the long-term data, the SODAR usually measures lower values than those measured by the cup anemometer.

The deviation: $v_{SODAR} = v_{anemometer} - 0.7 \pm 0.4\ m/s$

In the top wind-velocity classes, in the range $3\ m/s \leq v_{SODAR} \leq 8\ m/s$, the error of the deviation progressively decreases.

7) According to the wind-profile investigations, taking the Hungarian orographic conditions into consideration, the expectable increase in the energy production of wind generators is –

$$E_{\text{yield change}} \cong 0.05 \bullet E_{\text{hub}} / 10 \text{ m}$$

up to the height of 210 m.

8) On the basis of the measurements carried out in more sites at long distances from each other in Hungary, the energy yield of the wind energy utilization can be forecasted.

5 Conclusions and suggestions

In the course of the calibration tests of anemometers, I concluded on that the sensors cannot provide the accuracy rated by the manufacturers in some cases, in a two-year period; accordingly, in the second year of use, it is reasonable to calibrate them more times or to exchange their bearings already after the first year.

The expectable dynamic increase in the investments in the wind energy utilization should require constructing a standard wind tunnel in Hungary as well which is suitable also for calibration of the anemometers applied in this field of the energetics.

For the sake of perfecting the completed wind chart, it would be reasonable to establish a national energetic-purpose wind-measurement network with measuring towers of 80 to 100-m height for measurements at minimum three level heights. With the help of this, an essentially more accurate mapping could be effected, than the present raster of 5 × 5 km.

This measuring station network, with a suitable computer hardware background, would be capable of forecasting the expectable energy yield of the whole country. With its help, the load variations in the mains caused by the operation of the wind generators could be reduced significantly. There are good examples of this in those countries of the European Union where the role of the wind-power plants is considerable in the electric energy supply.

For the establishment of the station network, the local relief conditions and the cover of the land are always to be taken into consideration. A denser station-site raster is reasonable in the fissured fields of changeable cover.

In addition to this, it is reasonable to take the location of the already existing and expectably erected larger wind-power farms in order to gain information concerning the energy producing site.

The erection close to the existing wind-power parks provides additional information for the erection of wind-power generators in group; it can be utilized for increasing in the efficiency of the erection and the operation.

During the operation of the measuring system SODAR applied for energetic wind measurements, it would be reasonable to measure much more meteorological factors (temperature, humidity, barometric pressure, amount of precipitation, duration of sunshine in hours etc.) and the ambient noise in order that the cause of the data-absence failures as well as the number of the factors influencing the operation including the degree of influence shall be determined.

In addition to this, it would be reasonable to calibrate the instrument for the possibly most level before each putting-in-action – with the help of calibrated or rather standard anemometers used in energetic wind measurements.

I reaffirm the earlier establishments on the tower heights applied in the erection projects of wind-power plants (h_{min} = 100 m; Tóth, 2005) and I amplify this with the suggestion that it is reasonable to apply the technically developed highest pylons in every case, under continental conditions.

6 Summary

In the research period, the process of the utilization of the wind energy started at a great pace in Hungary. The nominal electric power capacity of the wind – power plants exceeds 60 MW in 2007. The objective is to establish a capacity of 330 MW up to 2010.

All these show how actual the subject of the dissertation is.

During my work, after the review of the professional literature sources in connection with the objectives aimed at, as the first step, I contributed to the construction of wind tunnel suitable for calibrating cup anemometers used in energetic wind measurements. Its availability proved to be basically important in terms of the later research tasks. During the calibration of the anemometers it proved clear that the calibration of the instruments (or at least recording their calibration relationship) is necessary not only before but after the on-the-spot measurements as well.

I extended the series of the wind energetic measurements to the whole area of the country in order to compare the regions with different orographic and meteorological features, and to collect information about the similar areas, as much as possible.

The measurement data and the results of their evaluation were used in the construction of the first wind chart of Hungary based on energetic wind measurements at more base points. In the course of mapping several advantages as well as disadvantages of the measurement data base became clear. I have managed to establish which measurement systems are reasonable to use under the different orographic conditions, and at what distance the gained data can be applicable in the ambient areas.

Due to the large number of the measurement sites, I managed to analyse the characteristic areas in Hungary, suitable for wind-energy utilization. With the help of these, I could extract general conclusions for the assemblage of the measurement system to be used in the case of an actual measurement environment, and in connection with the evaluation of the data.

I obtained further general information in the field of the calculation of the energy yield and the prognostic possibilities. These are continuously debated issues in terms of both the economy and the operating of the electric power network.

In conclusion, I managed to establish under what conditions the measurement system and the connected software package used by me can be applied in Hungary and I extracted several general conclusions from the gained data in terms of the domestic utilization of the wind energy, with an acceptable success.

7 Publications concerning the field of the dissertation

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