MSc Program
Renewable Energy in Central and Eastern Europe

Influence of Thermal Stratification on the Vertical Wind Profile

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by

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Salzburg, March 2012

Affidavit

I, **Katharina Tiefenbacher,** hereby declare

1. that I am the sole author of the present Master Thesis, "Influence of thermal stratification on the vertical wind profile", 51 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

Vienna, _____ _____

Date Signature

Preface

This thesis was prepared in conjunction with both the Austrian University of Technology in Vienna and the consulting engineers for renewable energy "Energiewerkstatt Verein" in Heiligenstatt-Friedburg, Upper Austria.

I would like to thank the university staff of the Master Program "Renewable Energy in Central & Eastern Europe" for being so supportive.

Also like to thank my supervisor, Andreas Krenn, for his critical comments and good advice concerning my work and writing; a very big thank you to my boss, Hans Winkelmeier, for his support and creative ideas in the analysis and writing process. I am also indebted to my colleagues for all their backing and the encouraging environment they helped create for me.

Many thanks to the owners of the wind measurement data I used here in an anonymized form. Without their permission this master thesis would not have been possible.

A special thank is due to Carol Ritter for her great support in helping to improve my English expression in this master thesis.

Thanks to my best friends for their enthusiasm and positive energy during this cold de-motivating part of the year.

I wish to send my warmest thanks to my family who have always supported me through all my endeavours. Finally, I would especially like to thank my partner Markus for his patience and understanding.

Katharina Tiefenbacher

Salzburg, March 2012

Abstract

The effect of vertical wind profile on the energy yield of wind turbines is well known. This profile is usually defined by orography and the surface roughness of the surrounding area. The influence of thermal stratifications however, is not taken directly into account. This leads to the core question of this thesis: Does this non-observance provoke errors in the wind power calculation, especially in areas with distinct thermal stratifications such as the Marchfeld region? Therefore, two different methods for determining stratification were utilised for evaluation of four different seasonal LIDAR measurement periods. The assumption that thermal stratification could have such significant influence on the vertical wind profile, making an observation necessary was confirmed. Unfortunately, the applied methods to observe the stratification failed. The results of this thesis point out that an urgent need for new methods to observe stratification does exist.

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Acronyms

DEWI ..... "**De**utsches **W**indenergie **I**nstitut" – German Wind Energy Institute

GPRS ..... **G**eneral **P**acket and **R**adio **S**ervice

GSM ..... **G**lobal **S**ystem for Mobile **C**ommunications

LIDAR ..... **Li**ght **D**etection **a**nd **R**anging

WEC ..... **W**ind **E**nergy **C**onverter

WM ..... **W**ind **M**easurement

ZAMG ..... "**Z**entral**a**nstalt für **M**eteorologie und **G**eodynamik" – Central Institute for Meteorology and Geodynamics

z0 ..... Roughness Length

Δθ ..... Potential Temperature Difference

1 Introduction

This master thesis focuses on the influence of the time-dependent variation of thermal stratification pertaining to vertical wind profile.

The main thrust of “Energiewerkstatt Verein”, the engineering consulting company that I am working for, is wind power. One part of this business is the energy yield assessment for planned wind turbines. For this evaluation knowledge of the vertical wind profile from ground level to blade tip is necessary. There is a standardized approach to calculate the vertical wind profile. This method does not take into account the influence of thermal stratification on the profile. In certain areas the vertical wind profile varies tremendously depending upon the thermal situation.

Our company has often worked on projects in areas with such strong characteristics of thermal stratification. Therefore, the question of verification in standard method accuracy arises in these areas. Especially when using short measurement systems such as LIDAR, consideration of the time-dependent variation of thermal stratification could be very important.

This master thesis deals with the following main questions:

- Does the thermal stratification have a significant influence on the vertical wind profile that observation is necessary in the calculation, especially in the Marchfeld region? Would a closer look on this influence provide more accurate results?
- If this assumption is confirmed, how should short time wind measurement data be evaluated in order to reach long-term average data related to the seasonal dependence of thermal stratification?

2 Theoretical Basics

This master thesis consists of a theoretical and an empirical part. The basics of this master thesis are dealt with in the theoretical part.

2.1 Weather Basics

The creation of wind and thermal stratification is explained in the following part.

2.1.1 Wind Flows

The earth is covered with an atmosphere which is several kilometers deep. Wind is, besides of clouds, rain, sun, etc., part of weather in general. It occurs in the lower part of the atmosphere in what is called the troposphere, which is 10-15 km wide. The troposphere is composed of the free atmosphere and the boundary layer.
Wind movement is balanced through varying density and pressure. Wind is caused, for example, when large scale air streams move from high pressure areas to low pressure areas. This ensuing wind stream is also influenced by the Coriolis force. Local wind systems result through different strengths of warming in the neighbouring zones (hill/valley, land/sea). [Moll, 1990]

The wind closest to the ground is influenced by obstacles and surface roughness. High above the ground, the wind is no longer affected by surface conditions. This undisturbed stream is called geostrophic wind. Between these two layers is the atmospheric boundary layer where the wind velocity changes with height. The height of the atmospheric boundary layer depends strongly upon weather and air pressure conditions. It ranges from near ground levels to 100 m on clear nights and 2000 m on fine summer days. The atmospheric boundary layer consists of the Prandtl layer and the Ekman layer, which lies above the Prandtl layer. Wind velocity inside the Prandtl layer increases more rapidly. The width of this layer can vary very widely. During stable high pressure winter periods, the layer may be only 20 m wide. On strong, unstable summer days, the width could reach 150 m. In the Ekman layer obstacles and surface roughness have only a small impact on wind velocity. In general, deceleration of the air stream can only take place through the Coriolis force. Its width varies between 100 m and 2 km, depending upon daily variation and weather conditions.

The following figure shows the atmosphere's lower layers:

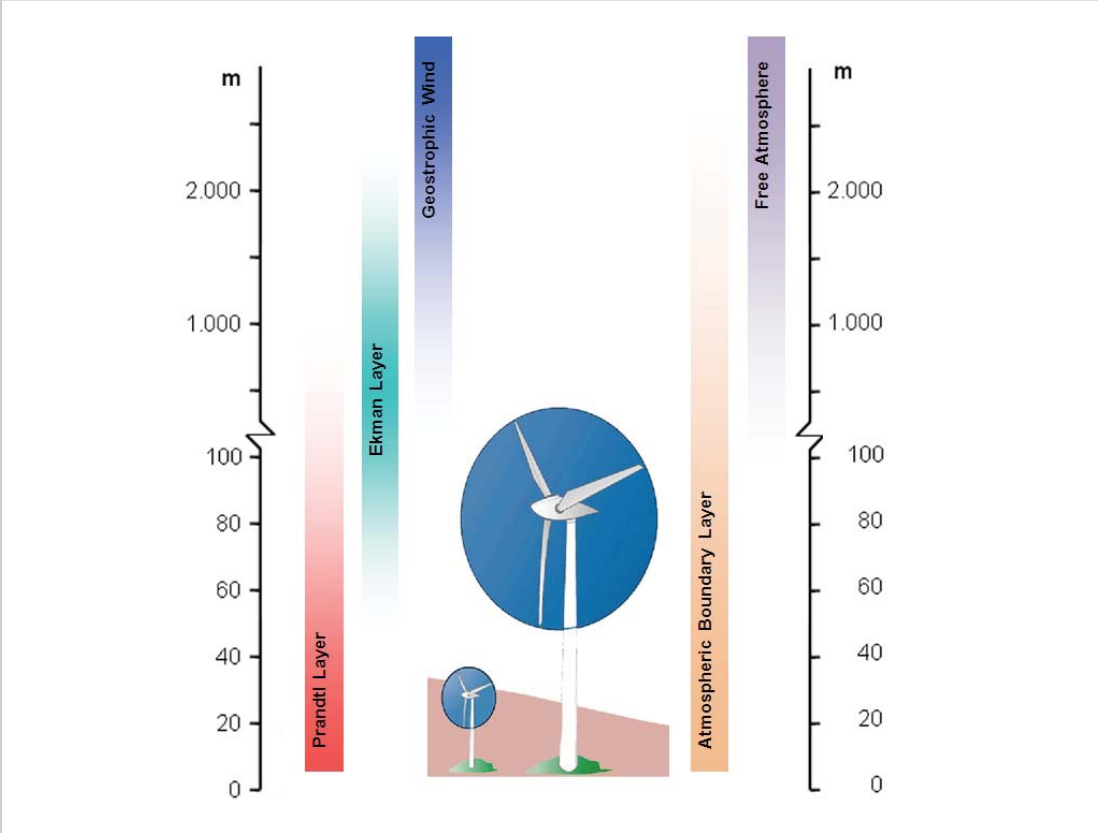


Figure 2.1-1: Layers of the lower atmosphere [Laye, 2012, modified]

2.1.2 Thermal Stratification

Thermal balance between higher and lower air layers has an effect on atmospheric stratification. Depending upon this equilibrium, a stable, a neutral (indifferent) or an unstable stratification arises. The formation of thermal stratification is based upon cold air's characteristic of having a greater density than warm air. This means that a balloon filled with cold air sinks; the same balloon filled with warm air climbs; the balloon filled with normal ambient temperature floats [Malb, 1997].

Rising air reaches lower external pressure, then expands and cools down. The opposite occurs in the case of a sinking air mass. It reaches higher external pressure, compresses, and consequently warms up. This process in the atmosphere is called adiabatic temperature change. Whether an air mass climbs, sinks or floats depends upon its density and its temperature in proportion to the ambient air. [Malb, 1997]

Unstable Stratification: The temperature in higher air layers is lower than the air temperature near the ground. The air mass near the ground climbs, however the higher positioned air mass sinks. This ensures a strong vertical mass exchange. In general, higher velocity occurs in higher altitudes. Because of this exchange, air masses reach the lower air layer. All vertical airflows, such as turbulence, are than increased. The additional turbulent mixing leads to a lower increase of wind velocity in relation to height. A reason for this situation could be a high solar irradiation, especially in summer months. [Strac, 1996] [Kren, 2010] [Gasc, 2010]

Stable Stratification: This form of stratification occurs mainly during the night and in the early morning hours, particularly in winter. In this case, the earth‘s surface has cooled down so much that it is unable to heat the overlying air layer. The temperature near the ground is higher than the air layers above. This ensures a low vertical mass exchange. A stable equilibrium occurs and vertical airflow is obstructed. The results are lower ground speed and strong wind velocity changes in the vertical line. In some cases, the stable stratification shows significant wind direction change in relation to height. [Strac, 1996] [Kren, 2010] [Gasc, 2010]

Neutral Stratification: A neutral (indifferent) stratification is a border case between unstable and stable stratification. Air masses set into motion will move uniformly, without vertical air movements (theoretical). In this case, a vertical wind profile can only be influenced by friction on the surface. It cannot now be influenced through thermal force caused by agitation. [Strac, 1996] [Kren, 2010] [Gasc, 2010]

Unstable and stable stratification situations are displayed in the following figure.

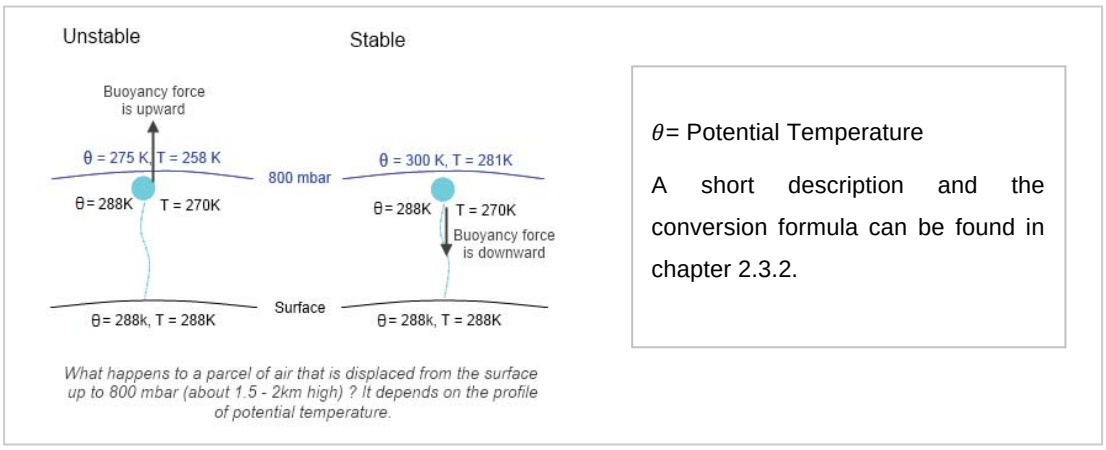


Figure 2.1-2: Unstable and stable stratification [Scie, 2012]

2.2 Basics for Wind Measurement and Wind Data Analysis

Beside a short introduction of wind measurement, the LIDAR measurement system is described in detail. The Alwin and Windpro analysis programs have also been utilized in this thesis and will be described in following paragraphs.

2.2.1 General Information of Wind Measurement

Most important for planning a wind turbine is knowledge of the wind situation in turbine height. In order to make predictions for expected wind speed, wind measurements over a longer time period are necessary. Measurements are required in order to make feasibility studies on wind turbine placement.

The most commonly used wind measurement system is the mast measurement. Varying forms of masts are equipped with anemometers and wind vanes. Often measurement systems for temperature, relative humidity and air pressure are also installed. Generally, cup anemometers are used for wind speed measurement. Ultrasonic anemometers offer a newer technology; the advantage is that the vertical and horizontal wind velocities are measured. The accuracy ratio is also higher.
The photography below shows the top of a measurement mast with cup anemometers and an ultrasonic anemometer.

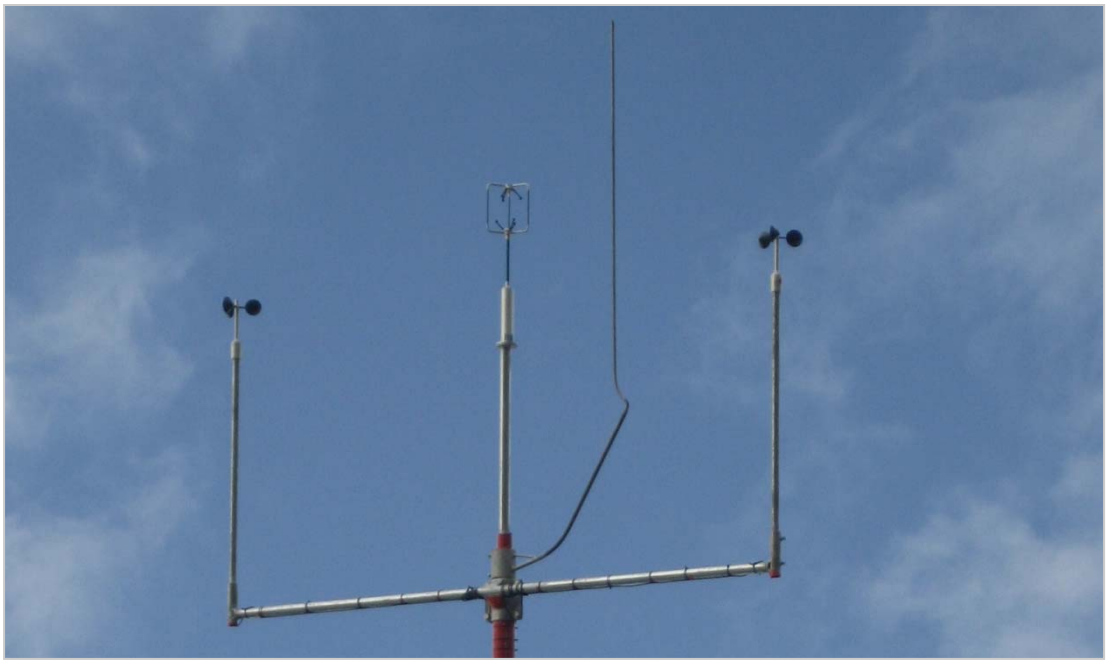


Figure 2.2-1: Visual of anemometers

2.2.2 Light Detection and Ranging (LIDAR)

Relatively new in wind energy sector is the measurement with LIDAR. It is an instrument for measuring atmospheric characteristics at various heights. They have been used in the wind power field for some years now to measure wind velocity and direction. The wind measurement LIDAR works as a Laser Doppler Anemometer. It uses the same principle as radar and emits laser pulses/waves. In the atmosphere, the signals are scattered back through particulate material. The aerosols move with the wind, whereby the backscattered light undergoes a frequency shift based upon the Doppler effect. LIDAR detects the backscattered radiation. The distance to the backscatter location can be calculated from the speed of light and the time of flight of the signals [Umas, 2011].

The following figure shows the function of a LIDAR system.

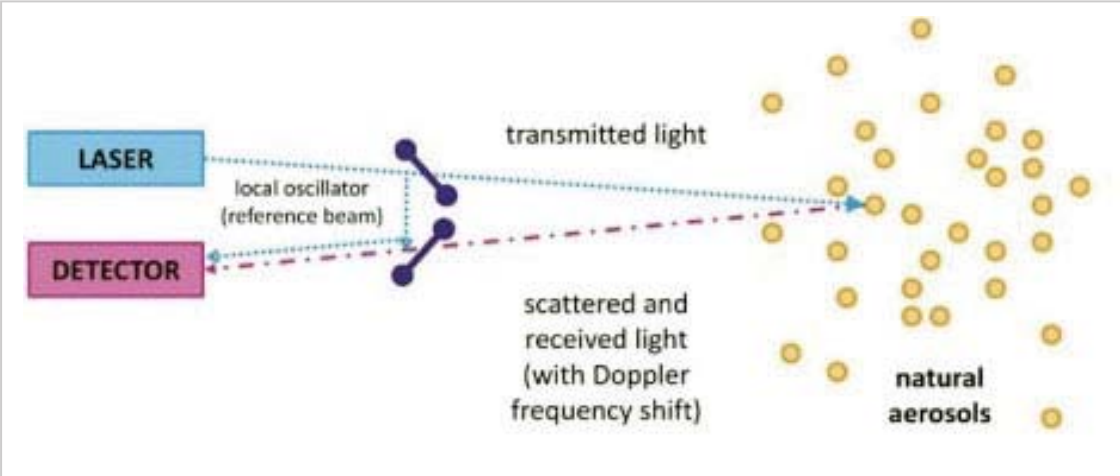


Figure 2.2-2: Function of a wind measurement LIDAR system [Umas, 2011]

Wind LIDARS available in the wind energy sector are based on two different measurement principles:

- Continuous Wave LIDARS (such as Zephir300 from Natural Power)
- Pulsed LIDARS (such as Windcube V2 from Leosphere)

The Pulsed LIDARS use signal timing to obtain vertical distance resolution, whereas Continuous Wave LIDARS are based on detector focusing. [Torb, 2009]

The following figures show the latest LIDAR Measurement systems of two market leaders in the wind energy sector.

Figure 2.2-3: Windcube V2 [Wind, 2012] and Zephir 300 [Zeph, 2012]

The typical LIDAR measurement system records the wind data in 10-minute intervals. The measurement levels lie between 40 and 200 m above the ground. Data is called up per GPRS. In good weather conditions data availability is between 95 % and 100 %.

One major advantage of the LIDAR system is its mobility. Wind velocities in heights of several hundred meters can be measured from ground level without the use of heavy measurement masts. The LIDAR measurement also provides a description of the vertical wind shear.

Disadvantages are acquisition costs, the complex procedure, and sensitivity to heavy fog, rain and clouds.

2.2.3 Weibull Distribution

The wind distribution is normally described through use of the the Weibull distribution. The curved form of the weibull function is described by Weibull parameters A and k. A is the scale parameter described in m/s. If the scale parameter is large, the distribtion will be more widely spread. A small scale parameter will lead to a more concentrated curve. The shape parameter k is dimensionless and an inverse measure of the variations of the wind velocity with respect to the mean.

The following formula describes the approximated relation between the Weibull parameters to the mean wind speed v.

$$v \approx A\sqrt[k]{0{,}287k^{-1}+0{,}688k^{-1}}$$

v……..mean wind velocity [m/s]

A…….scale parameter [m/s]

k……..shape parameter [-]

Formula 2.2-1: Weibull parameters

The following figure shows wind distributions with different A and k parameters.

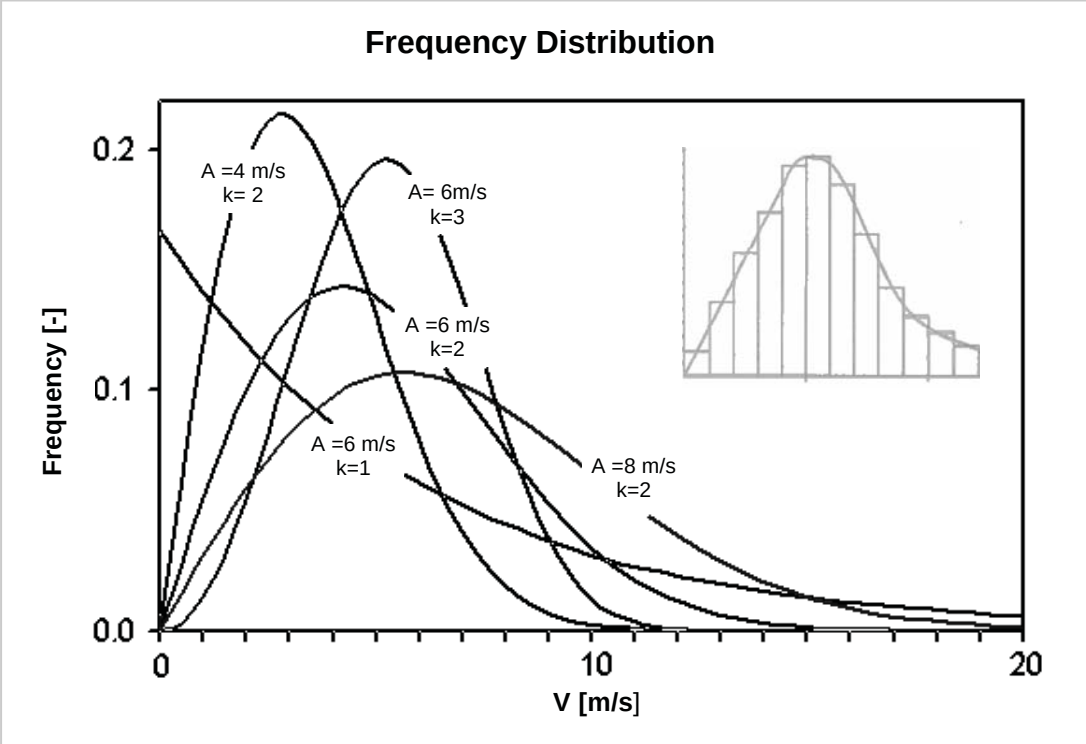


Figure 2.2-4: Wind speed distribution based on the Weibull function [Gasc, 2002, modified]

2.2.4 Wind Data Analysis Programs

There are now a large number of programs to create reliable wind prognoses. The following subchapters present a short description of two analysis programs, which were used in this study.

2.2.4.1 ALWIN

The small, one-dimensional program ALWIN was developed in cooperation with Dewi and Ammonit in 1993. Wind data is organized in site files and then presented in graphs, for example the frequency distributions and wind roses. Mean wind speed and the Weibull parameters can be calculated for a given wind speed distribution. The roughness length can be calculated using two wind speed data at different heights. The site data is then combined with wind turbine power curves for energy output calculations [Dewi, 2012].

The program is easy to handle, provides quick results, and is free of charge.

2.2.4.2 WINDPRO

WindPRO is a multi-dimensional software for the design, development and assessment of wind energy projects. The program is very extensive but more difficult to use. It consists of a number of modules (see the following figure). WindPRO was developed in Denmark and is based on more than twenty years of experience [emd, 2012].

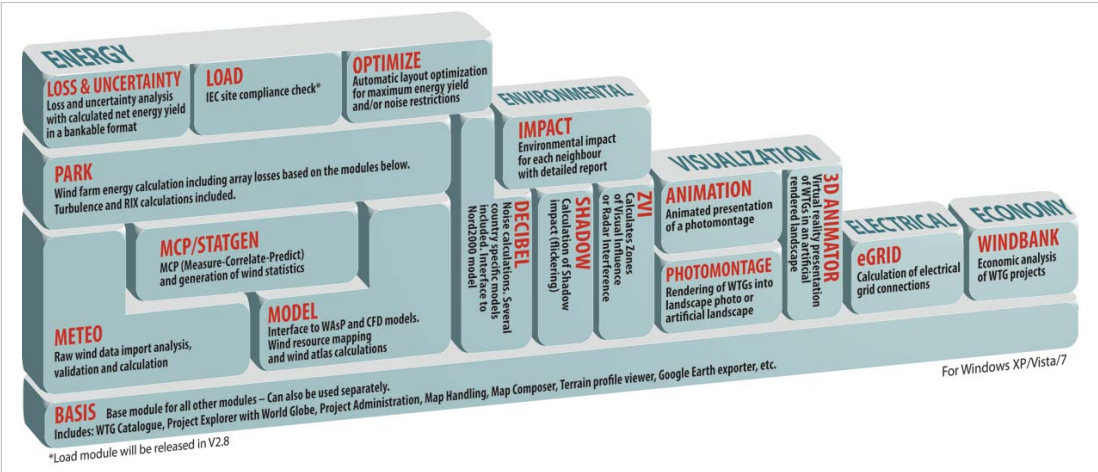


Figure 2.2-5: WindPro [emd, 2012]

2.3 Approximation Formulas

The following subsections explain the main formulas which were used in this master thesis. This includes mathematical descriptions of the vertical wind profile as well as approximation formulas for weather parameters such as temperature and pressure.

2.3.1 Vertical Wind Profile

The logarithmic wind law is a good approximation for the vertical wind profile in flat terrain and under neutral (indifferent) stratification. This equation provides good results for greater heights (over 100 m in a thick boundary layer).

The wind velocity decreases with diminishing height above the ground. The higher the degree of surface roughness, the stronger the decrease in velocity. The roughness length serves as a measurement for the roughness of the surface. [Moll, 1990]

Vertical wind profile formula:

$$\frac{v2}{v1} = \frac{ln\left(\frac{h2-d}{z0}\right)}{\ln\left(\frac{h1-d}{z0}\right)}$$

v_1……..Wind Velocity [m/s] at height h_1 [m]

v_2……..Wind Velocity [m/s] at height h_2 [m]

z_0……..Roughness Length (water surface ~ 10^{-4}, city-wood 1-5) [m]

d……Length showing the Offset of the Boundary Layer [m]

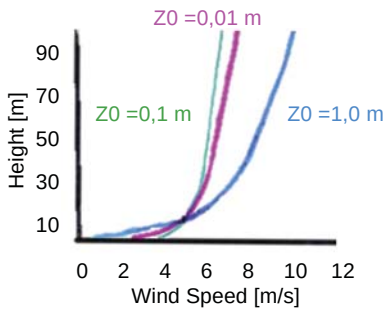
low vegetation and widely distributed obstacles = 0

for example, forests or city locations = 70 - 80 % of the obstacle height

Formula 2.3-1: Vertical wind profile

If the wind velocity is known at two altitudes, it can subsequently be calculated mathematically for all other altitudes. In case that only the wind velocity at one height is known, the wind speed can still be determined at other altitudes by estimating the roughness length z0. [Kren, 2010]

The following figure shows the vertical wind profiles, dependent upon the varying ground situation, and all with a wind speed of 5 m/s at 10 m of height



Z0 =0,01 [m] lawn, willow

Z0 =0,10 [m] bush-land

Z0=1,00 [m] towns, forest

Figure 2.3-1: Wind speed profiles for different roughness lengths

The vertical wind profile can also be estimated through Hellmann's power law [Moll, 1990]:

$$\frac{v2}{v1} = \left(\frac{h2}{h1}\right)^{a}$$

α ……..Hellmann Exponent

Formula 2.3-2: Vertical wind profile - Hellmann

There are different standard values for the Hellmann exponent depending upon the topography (Open Sea 10^{-3}, Wood 10^{-1}). The Hellmann exponent can also be determined through the mean wind speed measured at two heights [Moll, 1990].

In reality, however, the current vertical wind profile is not only influenced by surface roughness and obstacles. The thermal situation also affects the vertical wind profile. The next figure shows the profile depending upon the thermal stratification. Details concerning thermal stratification can be found in chapter 2.1.2.

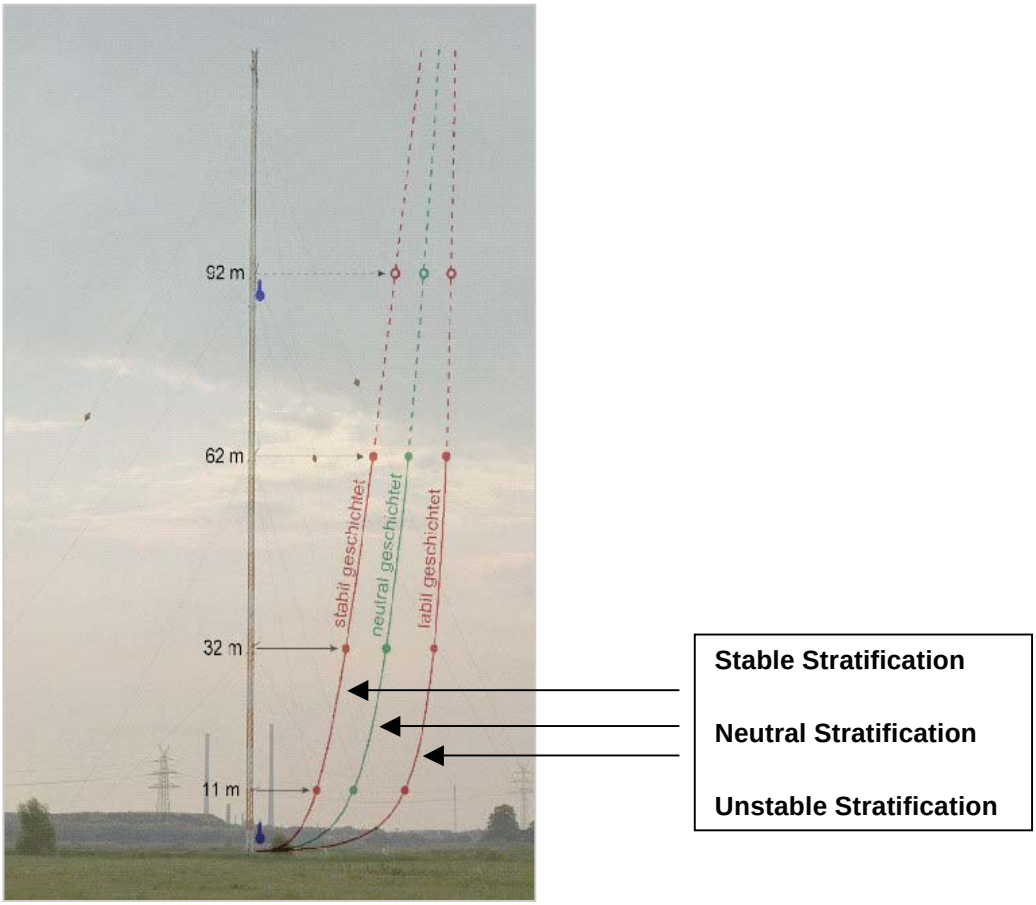


Figure 2.3-2: Vertical wind profile with stable and unstable stratification [Kren, 2010]

2.3.2 Potential Temperature

The potential temperature (θ) is used to make air temperatures at different heights comparable. This is the temperature that an air mass would reach if adiabatically brought to standard pressure. [Tech, 2012]

$$\theta = T_h \left(\frac{p_0}{p_h}\right)^{\frac{RL}{c_p}}$$

T_h……absolute temperature [K]

P_h……air pressure at base level [hPa]

P_0……standard pressure = 1013,25 [hPa]

R_L……specific gas constant of dry air = 287 [J/kg K]

c_p ……specific heat capacity at constant pressure = 1003 [J/kg K]

Formula 2.3-3: Potential temperature

2.3.3 Barometric Formula

The Barometric Formula describes air pressure depending upon height. This equation assumes that the temperature of the atmosphere is the same at all altitudes, which unfortunately is not always true. It is a model of an isothermal atmosphere [Baro, 2012]. It is only an approximate formula, but it is sufficiently accurate for the calculations in this master thesis.

$$p_h = p_{h_0} e^{-\frac{h}{h_s}} \qquad h_s = \frac{RT_p}{Mg} \approx 8km$$

P_h……Air Pressure at Base Level [hPa]
P_{h0}…….....Pressure at Sea Level = 1013,25 [hPa]
h…….....Height above Sea Level [m]
h_s…….....Atmospheric Scale Height [m]
M…….....Molar Mass of Earth's Air = 0,029 [kg/mol]
T_p…….....Mean Planetary Surface Temperature= 273,15 [K]
R…….....Gas Constant = 8,3145 [J/mol K]
g…….....Gravity at the Surface = 9,807[m/s^2]

Formula 2.3-4: Barometric formula

Hs ~8 km is a good approximate value for the whole atmosphere [Roed, 2000].

3 Empirical Analysis

The region where the measurement data for the evaluation originated is described in the following. A brief description of the pertinent data follows.

Subsequently, the different calculations of the new approach, taking stratification into consideration, are also described. These results are than compared to the conventional results. Ultimately, the most important outcomes are summarized.

3.1 Marchfeld Region

Data utilized for this evaluation originated from the Marchfeld region. This area was chosen due to its strong thermal stratification, beneficial flat ground with minimal surface roughness, and good wind power potential. A description of the Marchfeld region is provided below.

Marchfeld is a region at 417 m - 528 m above sea level and is the largest plain in Lower Austria. This large, gravel and “Tegel” plain of approximately 900 km^2 is also called Austria‘s “granary”. Geologically it belongs to the Vienna Basin. It is a subsidence area between the Eastern Alps and the Carpathians. The Marchfeld is bordered by the Danube River and its meadows in the south, the March/Morava River in the east, the hilly regions of the Weinviertel in the north and the Bisamberg Hill in the west.

The following map presents an overview of the Marchfeld.

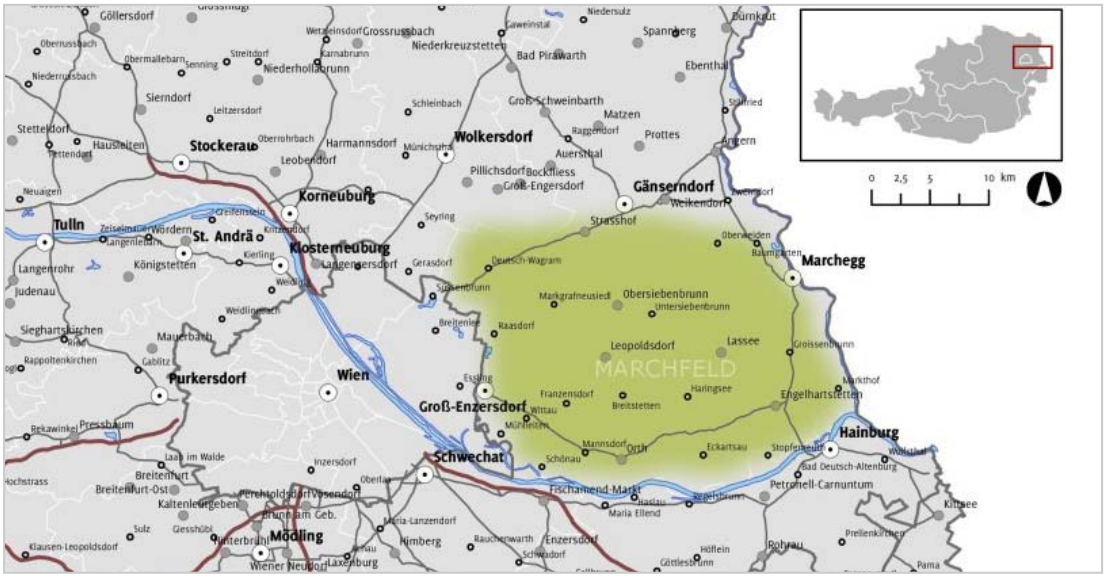


Figure 3.1-1: Overview map of the Marchfeld [Mubi, 2012]

The Marchfeld area is approximately 35 km long and 25 km wide. 190 km^2 are made up of river-meadows and provide a habitat for diverse wildlife. The northern parts consist of stretches of diluvial gravel partly covered with loess. A terrace (little Wagram) of roughly 10 m in height lies between the villages of Deutsch Wagram and Marchegg. This terrace divides the plain into the Upper and Lower Marchfeld Plain. Stretches of wind-borne sand, pine forests, meadowlands, fertile grain and sugar beet fields alternate in this area.

The sinking ground water level and the extensive agricultural exploitation led to an increase in barren territory and to a loss of 80% of the wetlands in the recent years. This results in lower water quality standards in the Marchfeld region [Aut2, 2012].

3.1.1 Marchfeld Climate and Wind Situation

Climatically, the Marchfeld lies in a transition region between the western European climate and the continental, eastern European climate. It is called the Pannonian climate. Characteristic for Marchfeld summers are much sunshine, high temperatures in summer with possible periods of drought up to three weeks. Cold and dry winters are also characteristic for this area. It is the driest and warmest zone in Austria.

Figure 3.1-2: Picture of the Marchfeld region [Aut3, 2012]

Strong winds are often further consequences of the excessive temperatures. The warm, often hot winds from the southeast play the most significant role for the wind production in the Marchfeld. The prevailing winds come from west and northwest. This mostly rain-laden, cold wind can be intensified through the nozzle effect of the "Wiener Pforte[1]". [Hada, 2000] [Aut, 2012]

Figure 3.1-3: Picture of the "Wiener Pforte" [Wien, 2012]

This region belongs to the best potential wind sites in Austria. As of the end of the first quarter of 2011, 39 wind turbines produced electricity on the Marchfeld's arable fields.

In order to get a good idea of the annual course of thermal stratification in the Marchfeld region, long-term data from the surrounding area was collected. The used long-term data originated from the Austrian Central Institute for Meteorology and Geodynamics - "ZAMG". Data from the years 1965 through 1983 was made available from four Vienna weather stations. The particularly high "Donauturm" measurement at 252 m was used principally and is important for the definition of the thermal stratification. Greater Vienna adjoins the Marchfeld region directly to the west. The measurement stations in Vienna are near enough to the Marchfeld region to make a good estimation of the thermal stratification annual course.

The principal information regarding long-term data can be found in the following table. An overview map with the stations follows.

[1] The "Wiener Pforte" is a gap where the Danube River breaks through into the Vienna basin. It is located between Leopoldsberg Hill and Kahlenberg Hill on the right side, and Bisamberg Hill on the left side of the river [Aut1, 2012].

Table 3.1-1: Description of the long-term data

Weather Station	**“Donauturm”**	**„Ringturm“**	**„Hohe Warte“**	**“Donaupark”**
Measurement Period	01.1965 – 12.1983	01.1965 – 12.1983	01.1981 – 12.1983	01.1966 – 10.1983
Sea Level	160 m	174 m	200 m	160 m
Wind Velocity Measurement	at 252 m	at 92 m	at 35 m	at 8 m
Wind Direction Measurement	at 252 m four sectors	at 92 m four sectors	at 35 m four sectors	at 8 m 32 sectors
Temperature Measurement	-	-	at 2 mt	-
Store Interval	one hour	one hour	one hour	one hour

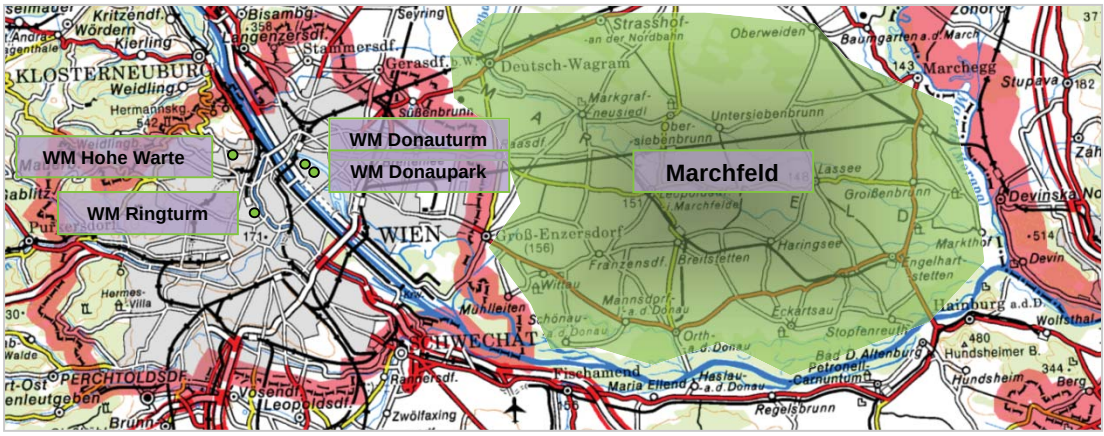


Figure 3.1-4: Weather stations - Long-term data [AMap; 2012, modified]

The following graphs project the daily behaviour of the long-term data for each month. The measurements from “Hohe Warte” and “Donaupark” in Vienna are shown in green and purple respectively. These measurements project no significant change in regards to monthly thermal stratification. Nevertheless, the typical behaviour of wind speeds at lower heights is shown. The speed increases around midday because of the strong vertical air mass exchange caused by the unstable stratification.

The red line represents the measurement “Donauturm”, the blue line “Ringturm”. These two measurements clearly demonstrate the monthly change of thermal stratification influence in relationship to each other.

A strengthened solar radiation occurs more often during the summer months than in the winter months. This leads to an increase in unstable stratification around midday. This can be easily seen in the wind speed time fluctuations from the "Donauturm" and the "Ringturm" series during the various months. From November through January, a clear decrease in influence is visible. The unstable stratification once again increases in the following months.

The following graphs show the daily course of the long-time data for each month. The X-axis represents time, the Y-axis the corresponding wind speed.

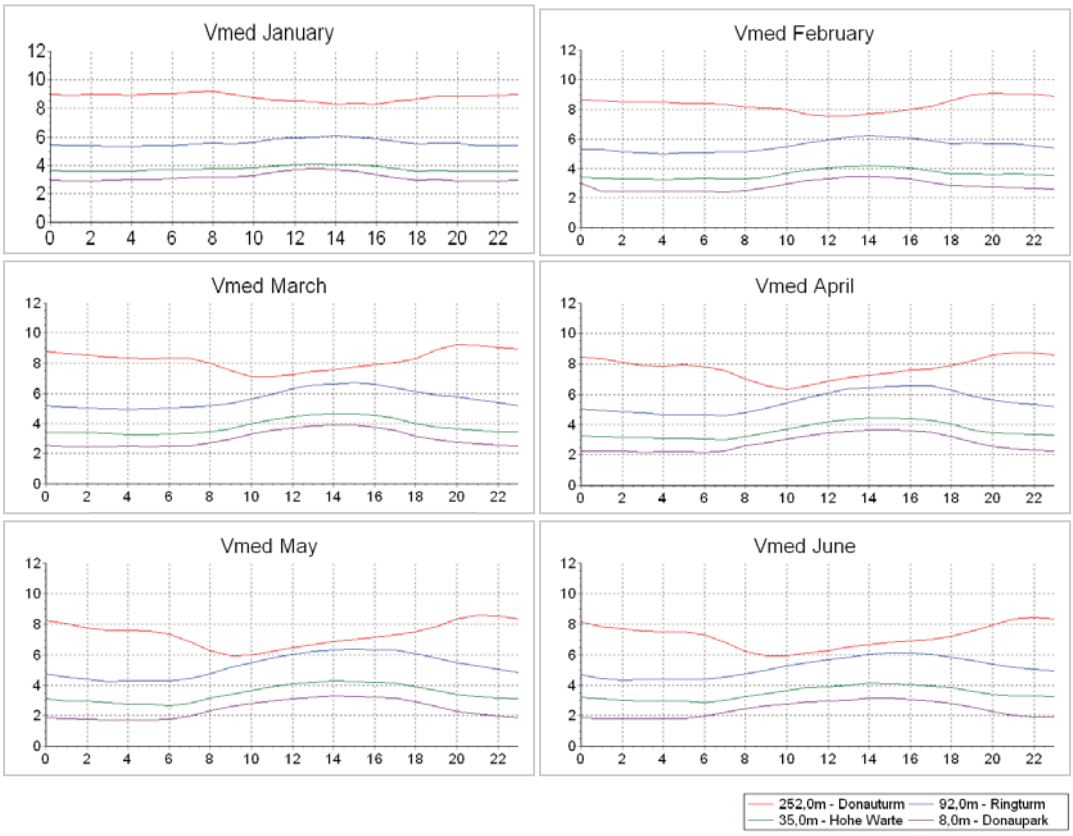


Figure 3.1-5: Daily course of long-term data for the months January - June

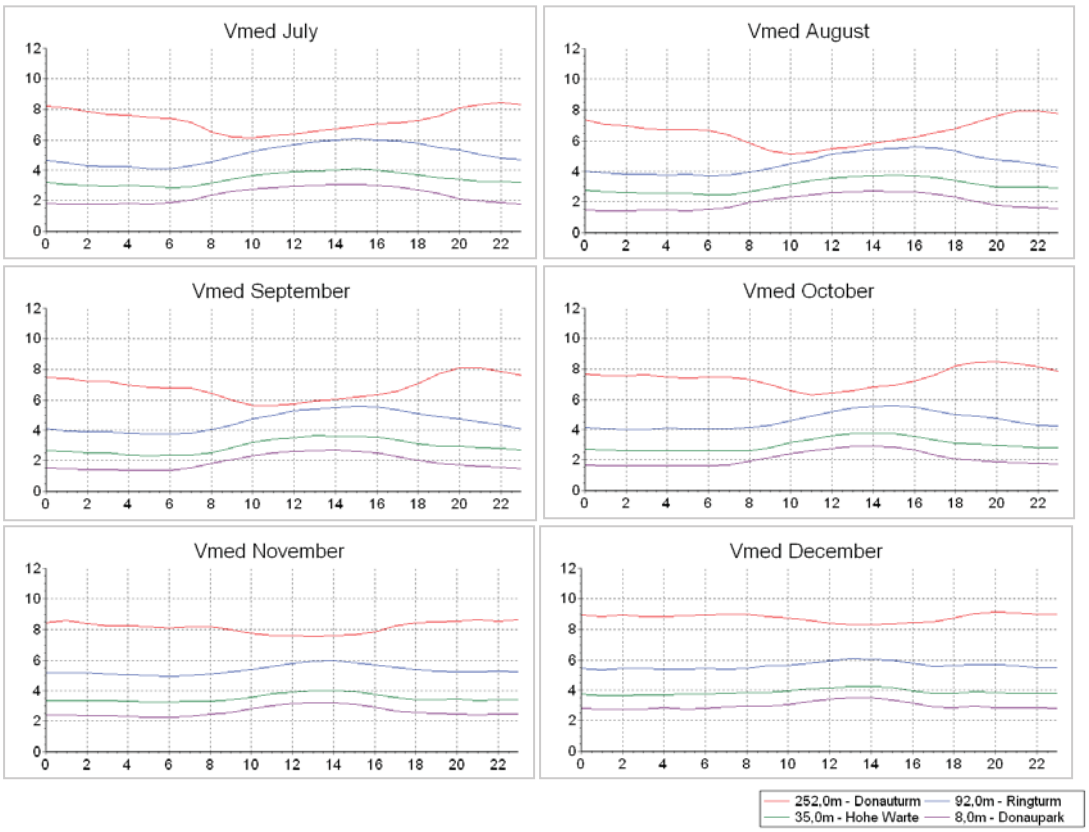


Figure 3.1-6: Daily course of long-term data for the months July - December

3.2 Data Basis

The applied data and their respective measurement systems are described in this chapter. The measured data is also presented.

Wind data analysed in this study comes from LIDAR measurements. The utilized temperature data originates from a mast measurement. All measurement systems were located in the Marchfeld area. The company “Energiewerkstatt Verein” provided the applied data. The data owners have allowed the usage of the required information, including essential conditions to anonymize the data. Due to this, dates, coordinates and sea level are not specified. Measurement height values are rounded and the location description is anonymized.

3.2.1 Measurement Systems

LIDAR measurements were carried out at this location in different seasons. This was done in order to assess the seasonality of the thermal stratification, and hence, the vertical wind profile in terms of seasonal time. The following table describes the construction and the configuration of the LIDAR measurements.

Table 3.2-1: Technical data of the wind measurement system

	Spring (LIDAR#1)	**Summer (LIDAR#2)**	**Autumn (LIDAR#3)**	**Winter (LIDAR#4)**
LIDAR Remote Sensor	Windcube V2	Windcube V1	Windcube V1	Windcube V2
Measurement Height	40m, 60m, 80m, 100m, 110m, 120m, 135m, 140m, 150m, 160m, 180m, 200m	40m, 60m, 80m, 100m, 110m, 120m, 140m, 160m, 180m, 200m	40m, 55m, 60m, 80 m, 100m, 120m, 140m, 160m, 180m, 200m	40m, 55m, 60m, 80m, 100m, 110m, 120m, 130m, 140m, 160m, 180m, 200m
Wind Signals	wind speed (mean, max, min, standard deviation) wind direction vertical wind speed availability within10min			
Accuracy Wind Speed	0,1 m/s	0,2 m/s	0,2 m/s	0,1 m/s
Accuracy Wind Direction	1,5°	2°	2°	1,5°
Sample Rate	1 second			
Store Interval	10 minute time series			
Data Transmission	GSM			
Power Supply	PV, diesel			

Two different LIDAR versions were put in place to measure the data used in this thesis. Both LIDAR versions are from the French company Leoshere, which is among the global market leaders providing LIDAR systems for wind measurements. The LIDAR measuring instrument “Windcube V1” and “Windcube V2” were used.

These two LIDAR versions differ slightly. “Windcube V2” has a higher wind speed accuracy and wind direction accuracy than its predecessor, and is more energy efficient. Both versions however, work with the same measurement system.

The following table describes the construction of a measurement mast. Only the temperature data was used in this study.

Table 3.2-2: Technical data of the temperature measurement system

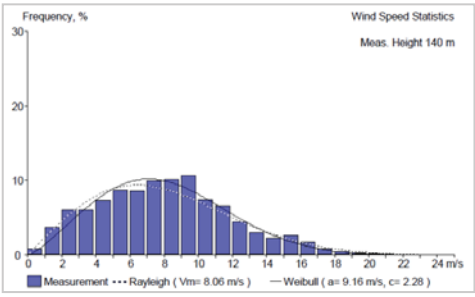
Mast Height	80 m
Wind Speed	four anemometers
Wind Direction	two wind vanes
Temperature	temperature sensor 1: measurement height 75 m type: Galltec PT100 temperature sensor 2: measurement height 6 m type: Galltec PT100

3.2.2 Measured Data

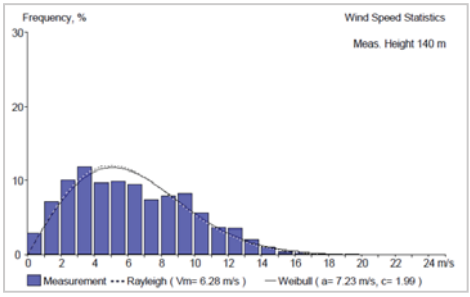
The tables below present the measured data at different heights, which was recorded with LIDAR systems during the relevant season. The figures on the right show the corresponding frequency distribution at 140 m of height.

Table 3.2-3: Overview of the measured values

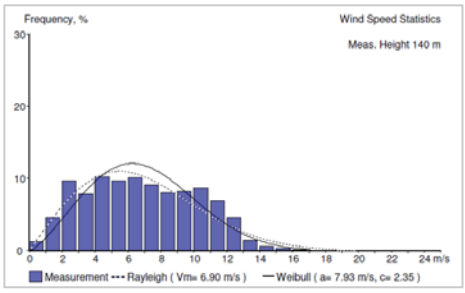
Period "Spring"					
Height	Values	V med	Weibull A	Weibull k	Roughness Length
[m]	[-]	[m/s]	[m/s]	[-]	[m]
40	5927	6,47	7,33	1,99	0,26
60	5927	6,88	7,79	2,08	
80	5927	7,24	8,21	2,14	
100	5927	7,52	8,53	2,18	
110	5927	7,66	8,66	2,17	
120	5927	7,80	8,83	2,20	
135	5927	8,00	9,09	2,27	
140	5927	8,06	9,16	2,28	



Period "Summer"					
Height	Values	V med	Weibull A	Weibull k	Roughness Length
[m]	[-]	[m/s]	[m/s]	[-]	[m]
40	6092	4,90	5,59	1,95	0,45
60	6092	5,35	6,13	2,00	
80	6092	5,64	6,48	2,01	
100	6092	5,87	6,77	2,02	
110	6092	5,98	6,90	2,01	
120	6092	6,09	7,04	2,01	
140	6092	6,28	7,23	1,99	



Period "Autumn"					
Height	Values	V med	Weibull A	Weibull k	Roughness Length
[m]	[-]	[m/s]	[m/s]	[-]	[m]
40	4451	4,58	5,28	2,28	2,97
55	4451	5,23	6,07	2,47	
60	4451	5,38	6,24	2,50	
80	4451	5,93	6,87	2,51	
100	4451	6,19	7,13	2,42	
120	4451	6,64	7,65	2,41	
140	4451	6,90	7,93	2,35	



Period "Winter"					
Height	Values	V med	Weibull A	Weibull k	Roughness Length
[m]	[-]	[m/s]	[m/s]	[-]	[m]
40	2312	5,11	5,88	2,29	3,06
55	2312	5,32	6,13	2,48	
60	2312	5,50	6,34	2,50	
80	2312	6,01	6,90	2,58	
100	2312	6,48	7,40	2,58	
110	2312	6,71	7,70	2,68	
120	2312	6,93	7,92	2,67	
130	2312	7,16	8,21	2,70	

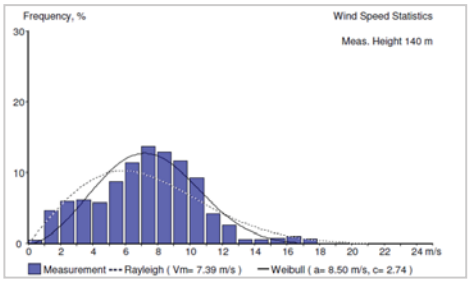


Figure 3.2-1: Frequency distributions of the wind speed at 140 m of height for each season [created by Alwin]

The following figure on the left hand side is a graphical presentation of the measured wind profiles normalized to 40 m of height. The graphs on the right show the daily course of the time series in different heights for each evaluation period.

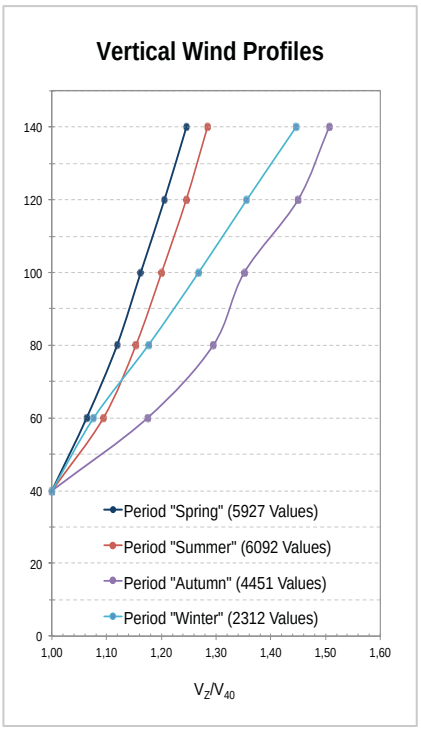


Figure 3.2-2: Vertical wind profiles for the different evaluation periods

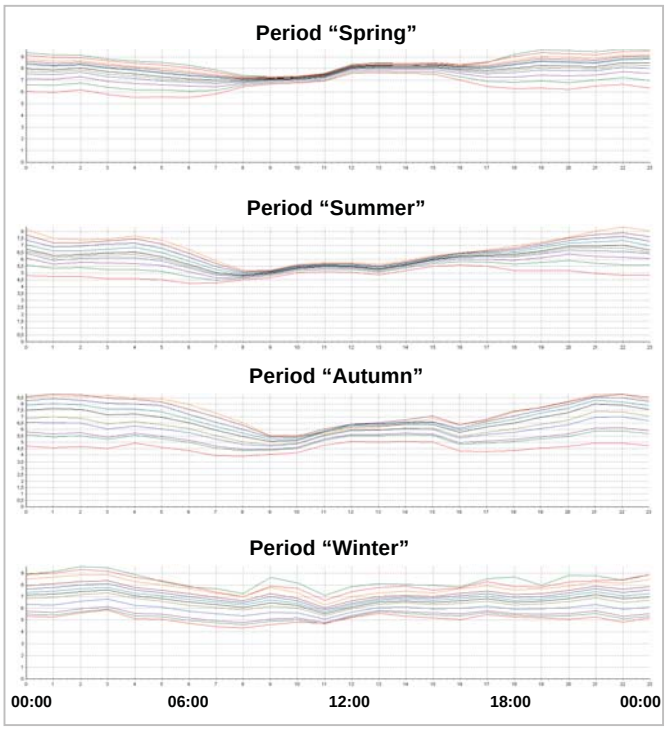


Figure 3.2-3: Daily course of the different evaluation periods [created by WindPro]

The values clearly show a strong unstable situation around midday during the spring and summer period, and thereby a slight increase in wind speeds with height. In the autumn, and mainly in the winter period, a stable situation dominates at midday. A strong increase of wind speed with height emerges. The reason for the seasonal difference is caused primarily by sun radiation, which occurs stronger in summer months than in winter months.

The measured vertical wind profiles in the spring and summer period is characterised by a logarithmic profile; the other two periods are not.

It is notable that during the night, the increase between the wind speed at 40 m and 80 m of height is much lower during the winter period than during the other seasonal periods.

3.3 Description of Calculation Method

Specific calculations made in this thesis will be explained in the following.

3.3.1 Determination of Thermal Stratification

The prime target of this master thesis is to evaluate the influence of thermal stratification on the vertical wind profile. To carry this out, means of determining the stratification over recorded data had to be defined. The two methods used in this thesis will be described in following paragraphs.

3.3.1.1 Determination through Temperature Values

One of the most commonly used methods in specifying the thermal situation is directly through the temperature situation at various heights. This requires a minimum of temperature values from at least two different heights.

The wind measurement data used in this thesis originates from LIDAR measurements. As usual with conventional LIDAR-measurements, no temperature was recorded in higher altitudes. The temperature data for this calculation came from a nearby mast measurement also installed in Marchfeld. It is highly likely that the temperature conditions are the same throughout the entire Marchfeld area, and this being the case, the distance between the LIDAR-measurement and the temperature measurement would represent no problem. A description of LIDAR and temperature measurement can be in found in the previous chapter (3.2).

In previous studies [Fock, 2003] dealing with the influence of thermal stratification on the vertical wind profile, the thermal situation is indicated through temperature in two heights.

Based on the DEWI study “Influence of Different Meteorological Conditions on the Power Performance of Large WECs” three different atmospheric stability situations are determined [Albe, 1996]. Therefore, the absolute temperatures (measured at 75m and 6m height) are converted into potential temperatures (θ). The thermal stratification is than determined by the difference between the two potential temperatures.

$$\Delta\theta = \theta\ 75m - \theta\ 6m\ [\mathrm{K}]$$

Δθ<= -0,25 [K] .....Unstable

-0,25 [K] < Δθ<0,25 [K].....Neutral

Δθ =>0,25 [K].....Stable

The evaluation based on the determination through temperature could only be realized for the periods “Autumn” and “Winter”. Only in these seasons, could the temperature measurement and the LIDAR measurement be used at the same time.

The formulas utilised, “Barometric Formula” and “Potential Temperature”, are described in chapter 2.3.2 and 2.3.3.

3.3.1.2 Determination through Roughness Length Values

The determination of the stratification utilising temperature is certainly the most precise definition. Since recording temperatures in wind measurements at two heights is relatively unusual, an additional method had to be found.

Due to the fact that thermal stratification is directly related to wind profile, a determination through roughness length zo was chosen. The zo was calculated using the 40 m data and the 80 m data for each measurement time frame. Subsequently, a classification was performed. Therefore, the behaviour of roughness length was observed during a period with both strong and low stratification influence. The daily course of wind velocity, roughness length and temperature difference is presented in the following two graphs.

The applied formula and description can be found in chapter 2.3.1.

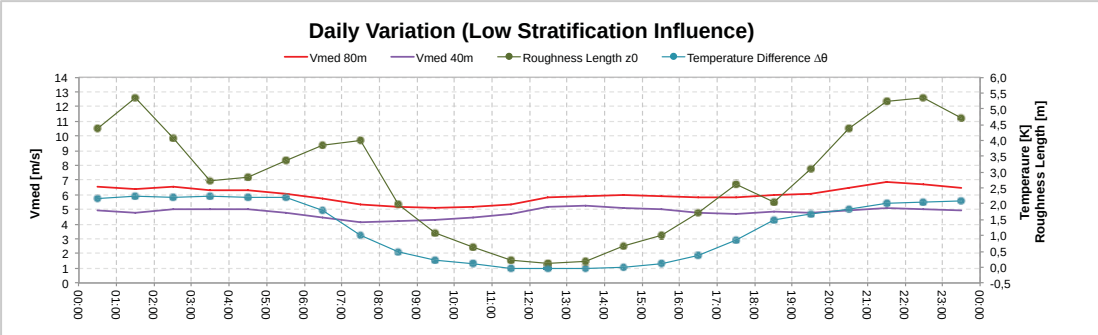


Figure 3.3-1: Daily course – Low stratification

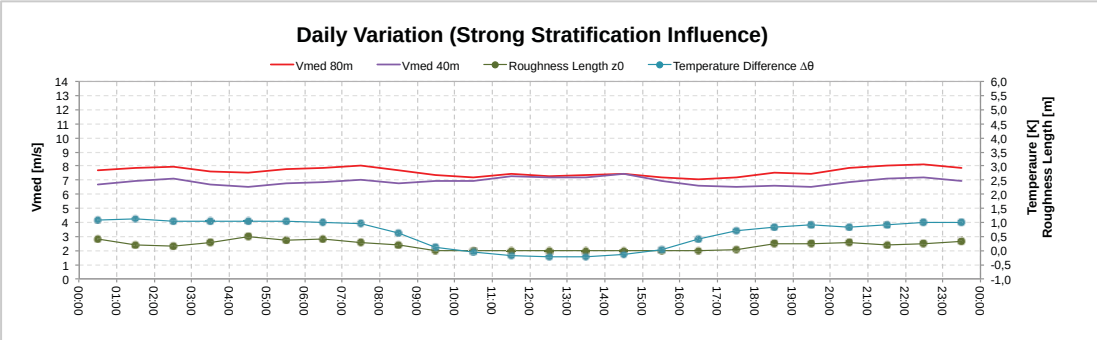


Figure 3.3-2: Daily course – Strong stratification

The classification was specified based upon the course of roughness length in different situations.

Classification according to thermal stratification:

z_0< 0,0001 [m]….....Unstable

0,0001 [m] <= z_0 <0,5 [m]…….....Neutral

0,5 [m] <= z_0 <40 [m]…….....Stable

3.3.1.3 Comparison

Here, the two thermal stratification determination methods are compared. Various graphs were made to provide a better overview regarding their behaviour and their relationship to each other. The most significant graphs are presented in the following.

The graph on the following page shows the interrelation between wind velocity, temperature and roughness length, taking thermal stratification into account. Wind speed and temperature are shown at different heights. The green line represents measurement values from 80 m of height; the blue line from 40 m of height. The calculated difference between the two potential temperatures and the calculated roughness length are shown in violet. The division into stable and unstable situations was carried out dependent on the behaviour of the wind speed time series.

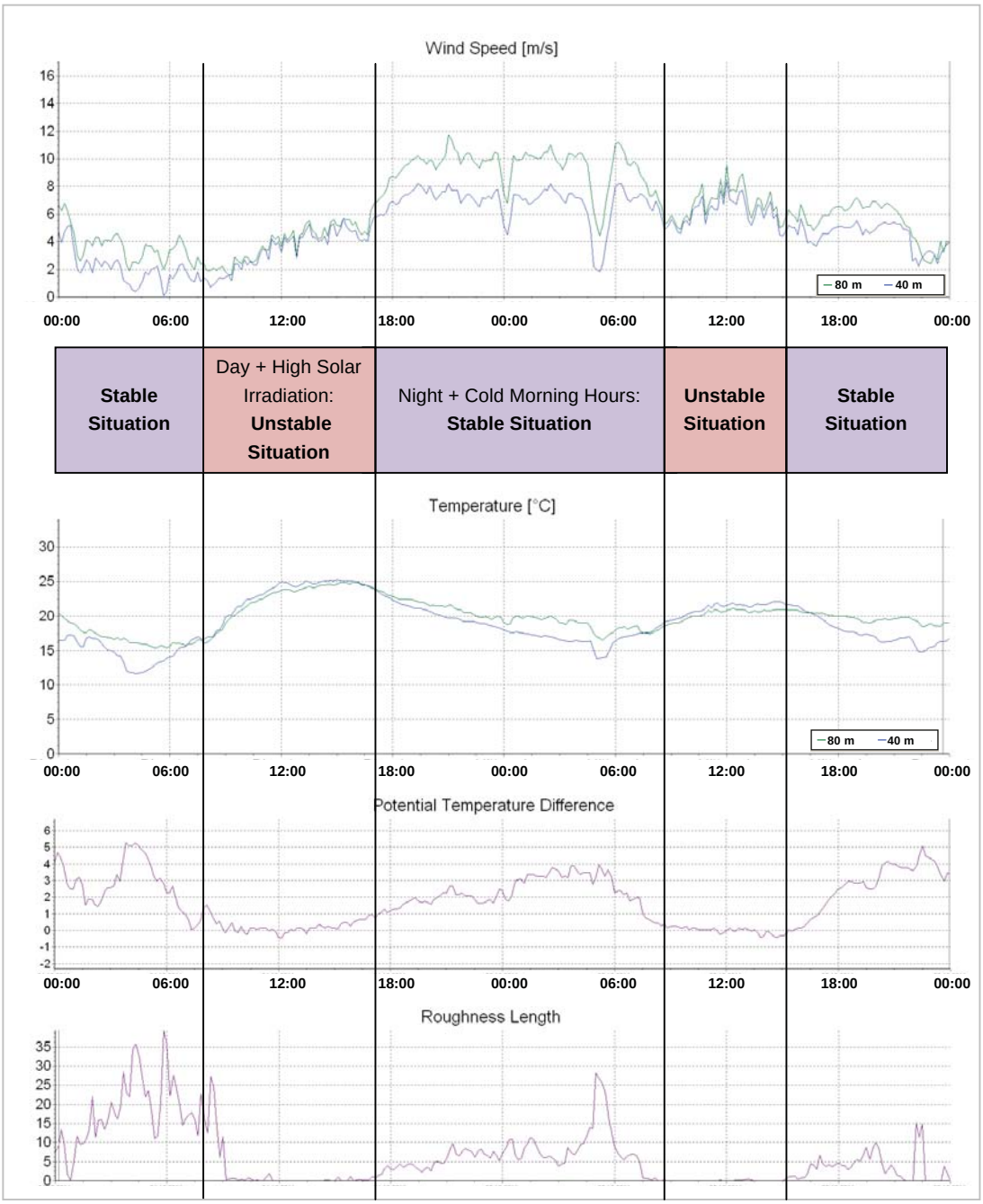


Figure 3.3-3: Wind velocity, temperature and roughness length behaviour dependent upon various thermal stratifications at Marchfeld [created by WindPro]

The previous graph also shows that during a strong stable or unstable stratification, both the determination through roughness length and temperature presents the same definitions of thermal stratification. The results tend to differ from each other during transitional periods. This is to be expected, as the roughness length depends upon various factors, rather than just thermal stratification.

The following figures present a further comparison of the two determination methods based upon the measured data. The left figure shows vertical wind profile for the entire evaluated period. In the figures on the right, the wind profile is separated into the three stratification situations; the top three with determination through roughness length, the bottom three through potential temperature. As mentioned above the two determination methods for thermal stratification give results with a greater variance, which is due mainly to differences during the transitional periods.

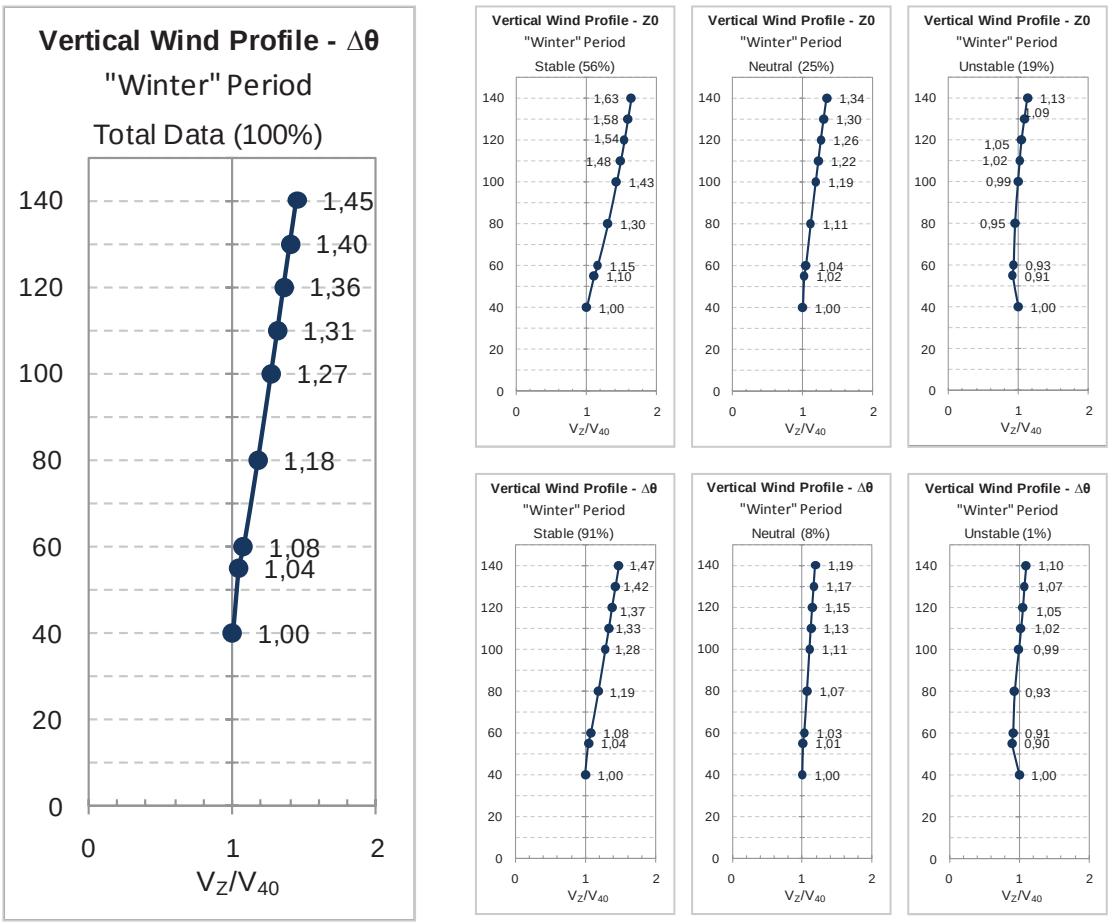


Figure 3.3-4: Measured vertical wind profiles “Winter” period

3.3.2 Main Calculations

The LIDAR measurements were deliberately carried out at different seasonal periods in order to measure the various stratification situations. Calculations for the measured period in spring, summer, autumn and winter were made separately. To assess thermal stratification influence on the vertical wind profile, data evaluations were done using different approaches; subsequently the results were compared to one another.

The target values are at 140 m of height. Therefore, the wind velocity at this height was calculated using the logarithmic wind law. Accordingly, the measured LIDAR wind data at heights of 40 and 80 m was needed.

Consequently the following values emerge.

- Energy yield at 140 m height
- Power density at 140 m height

The following three approaches were applied:

Calculation 1 (Neutral Profile): In the case where wind measurement at only one height is available, calculation 1 is used. A straight neutral profile is assumed. Here the values for 140 m were calculated using the data at 40 m of height and an estimated roughness length. A length of 0,12 m was assumed, based upon the surface roughness and obstacle.

Calculation 2 (Averaged Profile): If wind speed is measured at a minimum of two different heights, this calculation is quite often used. The wind data at heights of 40 and 80 m were used to calculate a roughness length. Through the use of these two measurement heights, an averaged (mixed) profile was calculated which is indirectly influenced by the thermal stratification. The calculated roughness length was then taken in order to quantify the wind situation at 140 m of height using the logarithmic wind profile.

Calculation 3 (Weighted Profile): In this case, the data was initially separated into the three thermal stratification classes; in calculation 3.1 using roughness length zo; in calculation 3.2 using temperature. Subsequently, the above mentioned values were calculated as in calculation 2, only here for each stratification class. The overall results were then evaluated by weighing the interim result. In this case the

thermal stratification is taken directly into account. Calculation 3.2 could only be realized for the autumn and winter period. During these periods, the temperature measurement and the LIDAR measurement were in use simultaneously. A detailed description of the determinations can be found in chapter 3.3.1.

The calculated wind velocities at 140 m of height using the three different methods were weighed against the accurate measured data at 140 m of height. Subsequently the resulting values (energy yield, power density) were compared.

To ensure accuracy, both programs Alwin and WindPro were used separately to calculate the energy yield and power density. The wind turbine “Enercon E82 2,3 MW” with a 140 m hub height was chosen for the wind energy yield calculation.

In order to ensure the highest level of comparability for this analysis, only data available at all three heights were used.

3.4 Results

In the following subchapter, the main calculation results are presented and separated into the “Spring”, “Summer”, “Autumn” and “Winter” measurement periods. The results are shown in tabular form. For a better overview, the results of measured data in 140 m height are presented in bold face and black. The results of the calculated data through the three methods are presented in bold face and red.

3.4.1.1 Results for LIDAR Measurement Period "Spring"

Here, the results from the "Spring" period are compared. During this time period the weather conditions were as follows:

A very slight increase in wind speed between 40 m and 80 m of height, followed by a stronger increase prevailed. Extreme unstable stratification due to sunny and dry weather conditions occurred during the midday time (see figure 3.2-3) [Zamg, 2012]. The conditions above resulted in a logarithmic profile. During this time period strong winds were inherent.

The following tables show the calculation results and the measured data for the "Spring" period.

Table 3.4-1: Results based on measured data "Spring"

Evaluation Period: LIDAR#1 - Spring		
Measured Data - Results based on Measured Data at 140m of Height		
Wind Speed at 140m of Height	Energy Yield at 140m of Height	Power Density at 140m of Height
[m/s]	[MWh]	[W/m²]
8,06	951	540

Table 3.4-2: Results based on calculated data "Spring"

Evaluation Period: LIDAR#1 - Spring										
Measured Data - Basis for Calculation								Calculated Data - Results based on Calculated Data - 140m Height		
Determination through	Based on Time Series	Values	Per cent	z0	V_{med}	A	k	V_{med}	Energy Yield	Power Density
[-]	[-]	[-]	[%]	[m]	[m/s]	[m/s]	[-]	[m/s]	[MWh]	[W/m²]
Calculation 1	Total 40m	5.927	100%	0,1200	6,47	7,34	1,99	7,87	896	566
Calculation 2	Total 80m	5.927	100%	0,1119	7,24	8,21	2,14	7,86	904	527
Calculation 3.1 Roughness Length	Neutral 80m	1.636	28%	0,0287	8,65	9,77	2,44	9,26	319	766
	Unstable 80m	2.490	42%	0,0000	6,86	7,76	1,90	7,11	318	437
	Stable 80m	1.801	30%	3,5678	6,49	7,38	2,77	7,66	257	410
		5.927	100%		7,24			7,87	894	520

The comparison of the results to their respective evaluation periods leads to the following findings:

- All calculated mean wind velocities at 140m of height (using all three methods separately) showed values approximating the measured value. The maximum variation came to 0,2 m/s.

- The comparison to energy yield and power density calculated separately using calculation 1, 2 and 3, also produced no clear distinction. Calculation 2 (Averaged Profile) showed slightly better values, without taking the thermal stratification into account. The results of calculation 1 (Neutral Profile) and 3.1 (Weighted Profile – z0) also provide acceptable values.
- Neither improvement, nor degradation appeared through thermal stratification observation. The calculated values using calculation 2 (Averaged Profile) achieved the real value quite accurately.
- Unexpectedly the neutral part, together with the unstable part, makes up more than 70 per cent of the time series.

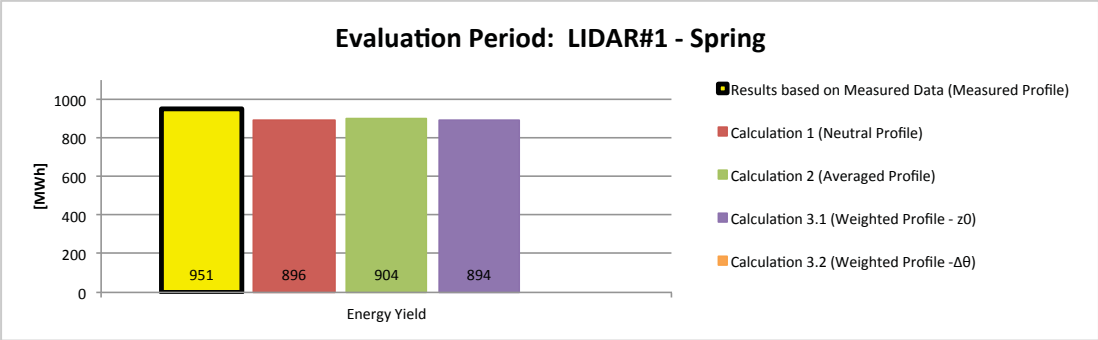


Figure 3.4-1: Energy yield results "Spring"

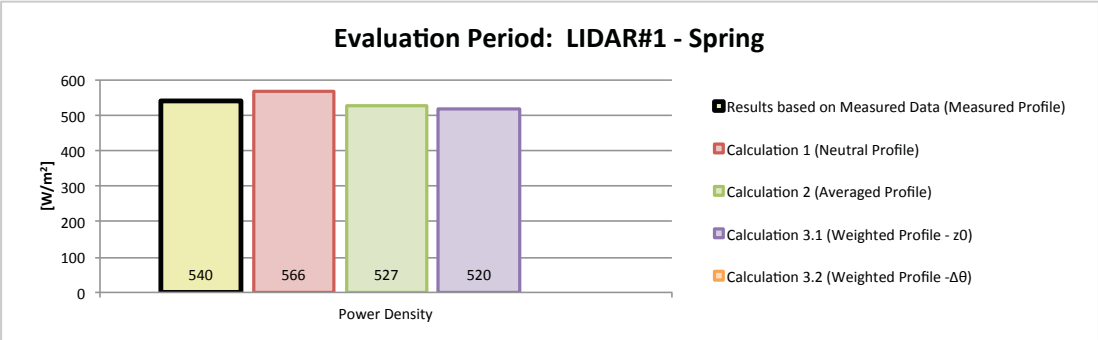


Figure 3.4-2: Power density results "Spring"

3.4.1.2 Results for LIDAR Measurement Period "Summer"

Here, the results from the "Summer" period are compared. During this time period the weather conditions were as follows:

Slight increases in wind speed between 40 m and 80 m of height prevailed. Unstable stratification due to many sunny, hot days occurred during the midday time (see figure 3.2-3) [Zamg, 2012]. Conditions here were not as extreme as in the "Spring" period. The conditions above resulted in a logarithmic profile. During this time period, moderate wind conditions were inherent.

The following tables show the calculation results and the measured data for the "Summer" period.

Table 3.4-3: Results based on measured data "Summer"

Evaluation Period: LIDAR#2 - Summer		
Measured Data - Results based on Measured Data at 140m of Height		
Wind Speed at 140m of Height	Energy Yield at 140m of Height	Power Density at 140m of Height
[m/s]	[MWh]	[W/m²]
6,28	638	296

Table 3.4-4: Results based on calculated data "Summer"

Evaluation Period: LIDAR#2 - Summer										
Measured Data - Basis for Calculation								Calculated Data - Results based on Calculated Data - 140m Height		
Determination through	Based on Time Series	Values	Per cent	z0	V_{med}	A	k	V_{med}	Energy Yield	Power Density
[-]	[-]	[-]	[%]	[m]	[m/s]	[m/s]	[-]	[m/s]	[MWh]	[W/m²]
Calculation 1	Total 40m	6.092	100%	0,1200	4,90	5,59	1,95	5,96	550	256
Calculation 2	Total 80m	6.092	100%	0,4975	5,64	6,48	2,01	6,26	624	291
Calculation 3.1 Roughness Length	Neutral 80m	1.594	26%	0,0400	6,41	7,10	1,95	6,88	187	362
	Unstable 80m	2.018	33%	0,0000	4,12	4,54	1,56	4,19	89	113
	Stable 80m	2.480	41%	3,8001	6,37	7,28	2,56	7,54	360	410
		6.092	100%		5,64			6,26	635	299

The comparison of the results to their respective evaluation periods leads to the following findings. Similar issues arise during the "Spring" period.

- All calculated mean wind velocities at 140 m of height (using all three methods separately) showed values approximating the measured value. The maximum variation came to 0,32 m/s.
- The energy yield and power density calculated through both calculation 2 (Averaged Profile) and calculation 3.1 (Weighted Profile – z0) also reached the target value quite well.

- Neither improvement, nor degradation appeared through thermal stratification observation. The calculated values through calculation 2 (Averaged Profile) achieved the real value quite accurately.
- Clearly exhibited is that the results of calculation 1 (Neutral Profile) presented the largest variance. All results from this method underestimated location during this period due to an actually larger roughness length.

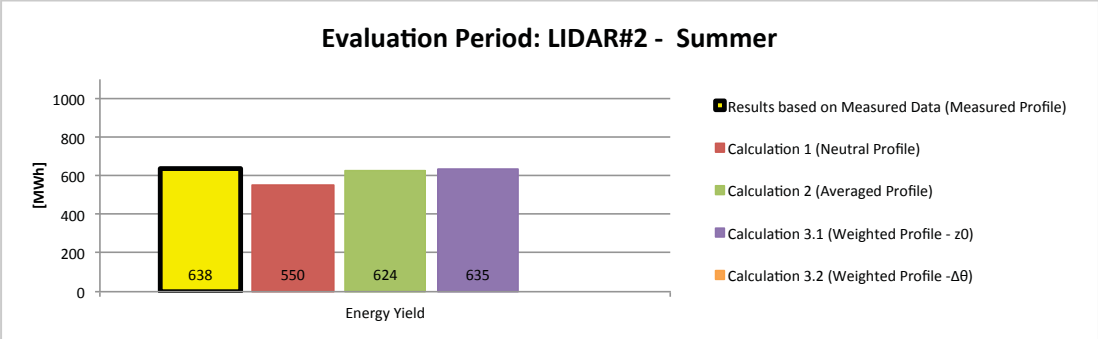


Figure 3.4-3: Energy yield results "Summer"

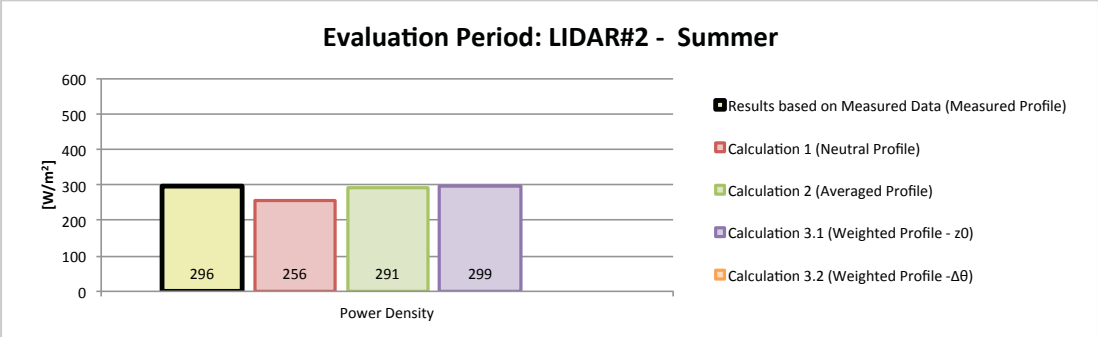


Figure 3.4-4: Power density results "Summer"

3.4.1.3 Results for LIDAR Measurement Period "Autumn"

Here, the results from the "Autumn" period are compared. During this time period the weather conditions were as follows:

Very strong increases in wind speed between 40 m and 80 m of height occurred, which then later decreased in power. Less unstable stratification took place during the midday time, in comparison to the "Spring" and "Summer" periods (see figure 3.2-3). Weather conditions were unusually warm and dry for this period [Zamg, 2012].

The following tables show the calculation results and the measured data for the "Autumn" period.

Table 3.4-5: Results based on measured data "Autumn"

Evaluation Period: LIDAR#3 - Autumn		
Measured Data - Results based on Measured Data at 140m of Height		
Wind Speed at 140m of Height	Energy Yield at 140m of Height	Power Density at 140m of Height
[m/s]	[MWh]	[W/m²]
6,90	542	337

Table 3.4-6: Results based on calculated data "Autumn"

Evaluation Period: LIDAR#3 - Autumn										
Measured Data - Basis for Calculation								Calculated Data - Results based on Calculated Data - 140m Height		
Determination through	Based on Time Series	Values	Per cent	z0	V_{med}	A	k	V_{med}	Energy Yield	Power Density
[-]	[-]	[-]	[%]	[m]	[m/s]	[m/s]	[-]	[m/s]	[MWh]	[W/m²]
Calculation 1	Total 40m	4.451	100%	0,1200	4,58	5,28	2,28	5,57	318	188
Calculation 2	Total 80m	4.451	100%	4,1272	5,93	6,87	2,51	7,05	557	356
Calculation 3.1 Roughness Length	Neutral 80m	778	17%	0,8043	5,41	6,09	1,91	6,07	65	270
	Unstable 80m	404	9%	0,0013	3,65	4,22	1,85	3,84	9	78
	Stable 80m	3.269	73%	5,4307	6,34	7,30	2,92	7,66	477	414
		4.451	100%		5,93			7,04	552	358
Calculation 3.2 Temperature	Neutral 80m	767	17%	1,1488	5,22	5,78	1,76	5,91	63	262
	Unstable 80m	553	12%	1,1385	5,19	5,97	2,10	5,87	36	247
	Stable 80m	3.131	70%	5,5278	6,24	7,24	2,97	7,55	450	402
		4.451	100%		5,93			7,06	548	358

The comparison of the results to their respective evaluation periods leads to the following findings.

- The calculated mean wind velocity at 140m of height, using calculation 2 (Averaged Profile), 3.1(Weighted Profile – z0), and 3.2 (Weighted Profile – t), showed values approximating the measured value. The maximum variation came to 0,07 m/s. The calculated wind speed using calculation 1 (Neutral Profile) showed a larger discrepancy.

- The comparison to energy yield and power density produced no clear distinction. The results of calculation 2, 3.1 and 3.2 are almost identical, and showed only a small variance to the results of the measured data
- Neither improvement, nor degradation appeared through thermal stratification observation.
- Clearly exhibited is that the results of calculation 1 (Neutral Profile) presented the largest variance. All results from this method underestimated location. The reason for the greater difference is that the actual roughness length is much higher than the estimation.
- The determination through roughness length and temperature provided similar results.

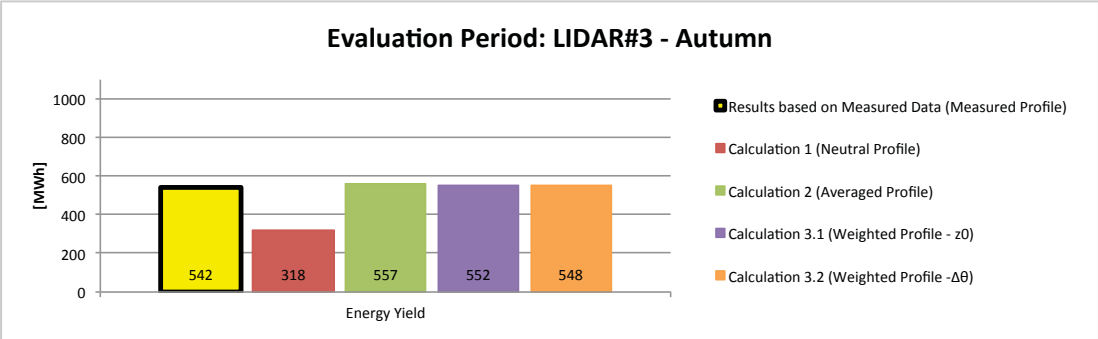


Figure 3.4-5: Energy yield results "Autumn"

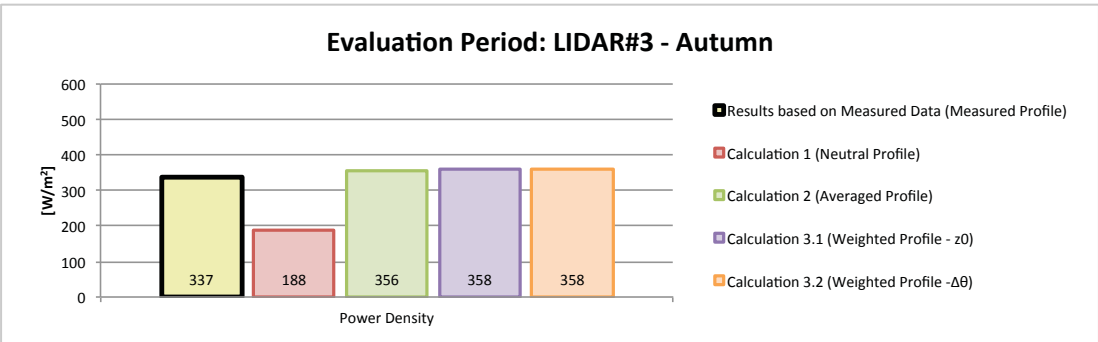


Figure 3.4-6: Power density results "Autumn"

3.4.1.4 Results for LIDAR Measurement Period "Winter"

Here, the results from the "Winter" period are compared. During this time period the weather conditions were as follows:

Powerful increases in wind speed between 40 m and 80 m of height occurred, followed by even more robust increases. Stable stratifications prevailed during the midday time (see figure 3.2-3). Weather conditions were unusually warm for this period, with little precipitation, and low wind conditions with little turbulence were inherent [Zamg, 2012].

The following tables show the calculation results and the measured data for the "Summer" period.

Table 3.4-7: Results based on measured data "Winter"

Evaluation Period: LIDAR#4 - Winter		
Measured Data - Results based on Measured Data at 140m of Height		
Wind Speed at 140m of Height	Energy Yield at 140m of Height	Power Density at 140m of Height
[m/s]	[MWh]	[W/m²]
7,39	313	383

Table 3.4-8: Results based on calculated data "Winter"

Evaluation Period: LIDAR#4 - Winter										
Measured Data - Basis for Calculation								Calculated Data - Results based on Calculated Data - 140m Height		
Determination through	Based on Time Series	Values	Per cent	z0	V_{med}	A	k	V_{med}	Energy Yield	Power Density
[-]	[-]	[-]	[%]	[m]	[m/s]	[m/s]	[-]	[m/s]	[MWh]	[W/m²]
Calculation 1	Total 40m	2.312	100%	0,1200	5,11	5,88	2,29	6,21	213	258
Calculation 2	Total 80m	2.312	100%	0,9425	6,01	6,90	2,58	6,77	252	306
Calculation 3.1 Roughness Length	Neutral 80m	572	25%	0,1058	7,13	7,92	2,52	7,73	60	433
	Unstable 80m	446	19%	0,0000	4,84	5,57	1,85	4,92	27	152
	Stable 80m	1.294	56%	3,7904	5,91	6,79	3,19	6,99	134	306
		2.312	100%		6,01			6,77	220	307
Calculation 3.2 Temperature	Neutral 80m	178	8%	0,0427	6,09	6,46	1,82	6,54	13	329
	Unstable 80m	30	1%	0,0000	2,69	3,41	2,58	2,74	0	24
	Stable 80m	2.104	91%	1,1746	6,05	6,97	2,71	6,85	229	310
		2.312	100%		6,01			6,77	242	308

The comparison of the results to their respective evaluation periods leads to the following findings.

- The calculated mean wind velocity at 140 m of height (using all calculation methods) showed lower values than the measured value. The variation came to 0,62 m/s. The calculated wind speed using calculation 1 (Neutral Profile)

showed a larger discrepancy at over 1 m/s caused by too little assumed roughness length.

- All results showed greater variance to the results of the measured data because the measured profile does not approximate a logarithmic curve.
- Neither improvement, nor degradation appeared through thermal stratification observation.
- Clearly exhibited, is that the results of calculation 1 (Neutral Profile) presented the largest variance. All results from this method underestimated location.
- The determination through roughness length and temperature provided different results.

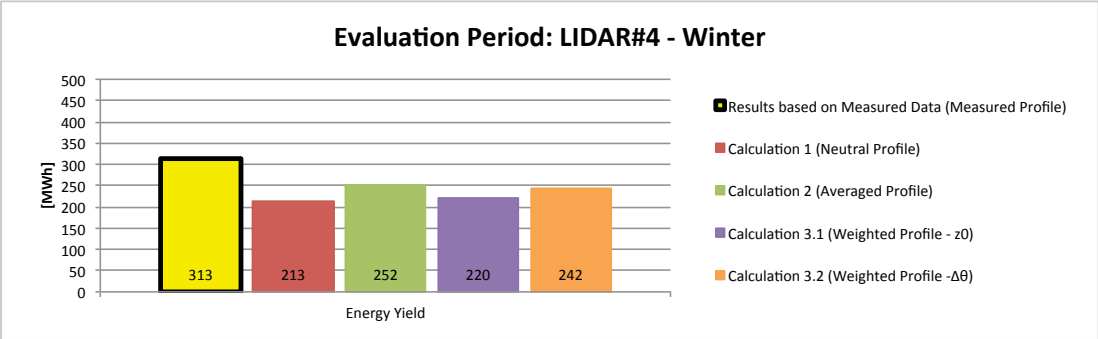


Figure 3.4-7: Energy yield results "Winter"

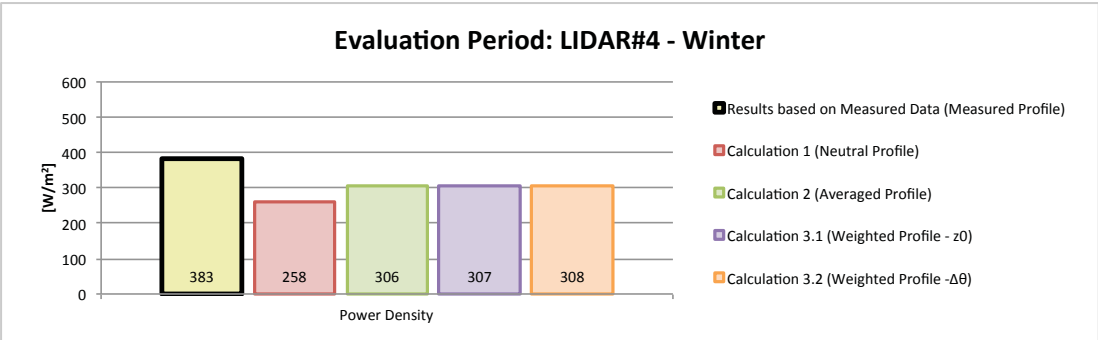


Figure 3.4-8: Power density results "Winter"

4 Conclusions

4.1 Conclusion for Question Number One

This section deals with the findings for the leading question number one in this thesis.

Question number one: “Does the thermal stratification have such a significant influence on the vertical wind profile that observation is necessary in the calculation, especially in the Marchfeld region? Would a closer look at this influence provide more accurate results?”

The following table gives an overview of the calculation results as to how the conclusions were formulated.

Table 4.1-1: Overview of the main results

	Period "Spring"			Period "Summer"			Period "Autumn"			Period "Winter"		
Number of Values	5.927			6.092			4.451			2.312		
z0 (40 m -140 m)	0,26			0,45			2,97			3,06		
	Vmed	Power Density	Energy Yield	Vmed	Power Density	Energy Yield	Vmed	Power Density	Energy Yield	Vmed	Power Density	Energy Yield
	[m/s]	[MWh]	[W/m²]	[m/s]	[MWh]	[W/m²]	[m/s]	[MWh]	[W/m²]	[m/s]	[MWh]	[W/m²]
Results based on Measured Data (Measured Profile)	8,06	951	540	6,28	638	296	6,90	542	337	7,39	313	383
Calculation 1 (Neutral Profile)	7,87	896	566	5,96	550	256	5,57	318	188	6,21	213	258
Calculation 2 (Average Profile)	7,86	904	527	6,26	624	291	7,05	557	356	6,77	252	306
Calculation 3.1 (Weighted Profile - z0)	7,87	894	520	6,26	635	299	7,04	552	358	6,77	220	307
Calculation 3.2 (Weighted Profile -Δθ)							7,06	548	358	6,77	242	308

Findings for the respective different calculations methods:

Calculation 1(Neutral Profile):

Based upon the surface roughness, a length of 0,12 m was assumed. The data from 40 m of height and the mentioned roughness length were used to calculate the values for 140 m of height. Only the results from the “Spring” period provided acceptable values compared to the target values. This was due to the extreme unstable stratification which occurred during this time. Only in this time frame did the assumed roughness length approximately match the actual roughness length. As expected, a method assuming a neutral profile is not suitable for this area.

Calculation 2 (Averaged Profile):

Based upon the values at 40m and 80m of height, a roughness length was evaluated. This roughness length was used to calculate the values for 140 m of height. For the “Spring”, “Summer”, and “Autumn” periods, the calculated and the measured wind speed were extremely close together. During these periods, even the result of energy yield and power density achieved entirely acceptable values. The situation during the “Winter” period was different. Here, this calculation method failed to approach the measured data and their respective energy and density results. During the “Spring” and “Summer” period, an almost logarithmic wind profile occurred. The profile for the “Autumn” period also showed a logarithmic increase from 80 m of height. This could be the reason for such good results in this period. Also the indirect influence of thermal stratification through the use of wind speed values from two heights had been underestimated. The stratification was more stable in the “Winter” period, hence the air was somewhat mixed and the vertical wind profile did not correspond to a logarithmic profile. Therefore the results failed.

Calculation 3 (Weighted Profile):

The calculated results by observation of the thermal stratification fell in the field of calculation 2 results (Averaged Profile), but showed no noticeable improvement. For the “Spring”, “Summer”, and “Autumn” periods, the results are closer to the target values. In the “Winter” period, the results failed. The determination using temperature and roughness length differed, but the results were similar. The determination through temperature is also used in other studies, and is in most cases, more exact then the calculation 3.2. However, in both cases the expected improvement through applied thermal stratification observation could not be confirmed. It appeared as if the applied thermal stratification observation did not lead to an improvement at the measurement location, at least not during the studied time frame.

The following general considerations were made:

- The indirect influence of thermal stratification through the use of wind speed values from two heights had been underestimated. Through this mixed profile, a good approximation for the vertical wind profile could be found, despite strong thermal stratification characteristics. This calculation worked quite well during

periods where much unstable stratification dominated, and an almost logarithmic wind profile occurred.

- The influence of thermal stratification is hard to pin down. The determination of the thermal situation through potential temperature or roughness length is only an approximation method. Not only the thermal situation, but also other weather conditions determine the behaviour of temperature and roughness length. The determination through temperature and roughness length differed strongly, and occurred mainly during the transitional periods of the stratification type.

After consideration of the first three seasonal periods, the answer to the leading question number one would have to be no. However, when including the “Winter” period, another understanding comes to light. The assumption that the thermal stratification would have such a significant influence on the vertical wind profile so that an observation is necessary, could be confirmed. This is applicable here only during the “Winter” period where an extreme stable stratification exists. The applied methods to observe the stratification failed during this period.

The results indicated that it would be important to measure the wind profile up to and including the hub height in these areas, for example with LIDAR measurements. This should be carried out mainly in stable situations, where the profile is primarily not logarithmic. Having this knowledge, it should be possible to find a method for application throughout the entire year. Therefore, a mast measurement is a necessity.

It is essential to assess each LIDAR measurement area separately, taking into account the influence of the thermal stratification. This can be done, as shown in my thesis, by calculating the values in hub height (here 140 m) using the measurement data from two different heights. If the results differ significantly from the measured values, a detailed observation of thermal stratification should be made. In future, I am certain that a better method to observe the stratification will be found. The results of this thesis show that an urgent need does indeed exist.

4.2 Conclusion for Question Number Two

The findings for the leading question number two are stated below.

Question number two: „How should short time wind measurement data be evaluated in order to reach long-term average data related to the seasonal dependence of thermal stratification?"

The assumption that the here used observation of stratification provides more accurate results, could not be confirmed. Consequently, the question regarding a time-dependent variation of thermal stratification is inapplicable.

In the case that another method for better defining the vertical wind profile at different stratification situations is found, the question of time-dependent variation gains in importance.

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