GIS-based Site Potential Analysis for Small-scale Wind Power Plants

by

Sandro Armando Arcidiacono

2nd Bachelor Thesis

Submitted in partial fulfillment of the requirement of the degree Bachelor of Science

Carinthia University of Applied Sciences
School of Geoinformation and Environmental Technologies

Supervisors

Internal Supervisor: Dr. Gernot Paulus
School of Geoinformation and Environmental Technologies,
Carinthia University of Applied Sciences, Villach, Austria

External Supervisor: Dr. Michael Leitner
Department of Geography and Anthropology, Louisiana State University,
Baton Rouge, Louisiana, United States of America

Baton Rouge, June 2012

Science Pledge

By my signature below, I certify that my thesis is entirely the result of my own work. I have cited all sources I have used in my thesis and I have always indicated their origin.

Villach, 06/14/12 S. Arcidiacono

Place, Date Signature

Acknowledgments

I would particularly like to thank my family, relatives and closest friends. The writing of this thesis would not have been possible without their continuous support and understanding.
I am sincerely grateful to my internal supervisor Dr. Gernot Paulus, School of Geoinformation and Environmental Technologies, Carinthia University of Applied Sciences in Villach, Austria for his constructive comments, detailed review and magnificent advice during the writing of this thesis.
I would like to show my gratitude to my external supervisor Dr. Michael Leitner, Department of Geography and Anthropology, Louisiana State University in Baton Rouge, Louisiana, United States of America, who gave me the opportunity to complete my internship at the Louisiana State University.
I would like to thank the Austrian Marshall Plan Foundation for their financial support that enabled me to fulfill my research for this Bachelor thesis at the Louisiana State University.
Finally, I would like to thank all other people who guided me through this thesis.

Zusammenfassung

Diese Bachelorarbeit befasst sich mit der Entwicklung und Implementierung eines konzeptionellen Modells zur Lokalisierung von geeigneten Installationsstandorten für Kleinwindkraftanlagen im Baton Rouger Vorort Park Forest/La North in Louisiana, USA. Die Entwicklung des Modells geschah in zwei Schritten. Der erste Schritt war es ein Entity Relationship Diagramm zu erstellen, welches das Verständnis der Beziehungen zwischen den einzelnen, in der Analyse betrachteten, Komponenten fördern soll. Schritt zwei inkludierte die eigentliche Erstellung des konzeptionellen Modells, wobei versucht wurde, jedes erwartete Resultat zu berücksichtigen. Das Modell wurde anschließend in ESRIs ArcGIS 10 implementiert. Die Resultate zeigen auf wo Windschatten durch Windhindernisse, wie Gebäude, Wälder oder Topographie, entstehen können und wo sich die besten Installationsstandorte für diverse Kleinwindkraftwerke befinden. Die dazu verwendeten Winddaten mussten vorher durch das Programm WindRose PRO3 von Enviroware aufbereitet werden. Dies geschah durch die Anwendung des Programms auf eine tabellarische Datei, welche die benötigten Winddaten enthielt. Dadurch entstand eine Windrose, aus welcher die Hauptwindrichtung und dessen Windstärke abgelesen werden konnte. Aufgrund von nicht vorhandenen LiDAR Daten musste die Höhe der Gebäude und Wälder im Untersuchungsgebiet Park Forest/La North durch eine Feldstudie geschätzt werden. Durch die ArcGIS Erweiterung „XTools Pro", welches von einer Drittperson entwickelt wurde, konnte die Windschattenkalkulation dennoch mit der benötigten Genauigkeit durchgeführt werden. Andere Faktoren, die das Endresultat des implementierten Modells beeinflussen, können anhand des am Ende des Arbeitsablaufes platzierten Raster Kalkulators gefiltert werden. Dies umfasst den geologischen Typ des Bodens, die Terrainhöhe, die Art der Landnutzung, die Distanz zum Stromnetz und die Toleranz für Windschatten. Da das Untersuchungsgebiet keine großen Höhenunterschiede enthält, wurde ein zweites angedacht, welches in Villach, Österreich liegen sollte. Dies wurde in dieser Arbeit nur theoretisch durchgedacht, jedoch nicht implementiert. Zusätzliche Faktoren, welche jedoch in dieser Arbeit nicht behandelt wurden, können mithilfe einer computerunterstützten Fluiddynamikanalyse mit ausreichender Genauigkeit berechnet werden. Darunter fallen die Beachtung eines Minimalabstands zwischen den Kleinwindkraftanlagen und eine zusätzliche Potentialanalyse für mögliche von Anlagen erzeugte Windschatten und dem Tunneleffekt, welcher bei hohen Gebäuden und Bergpässen auftreten kann.

Abstract

This thesis deals with the development and implementation of a conceptual model for locating suitable installation sites for small-scale wind power plants in the Baton Rouge suburb of Park Forest/La North in Louisiana, USA. The development of the model occurred in two steps. The first step was the creation of an Entity Relationship diagram to be able to understand the relationships between the components that are affected by the analysis. Step two includes the development of a conceptual model that ensures a high potential of applicability. This model has been implemented using ESRI's ArcGIS 10. The results show the locations of slipstreams occurring from wind obstacles and suitable places for locating different small-scale turbines. The wind data has been preprocessed with the help of the program WindRose PRO3 from Enviroware. This program is able to transform comma separated value files into a wind rose, so that the main wind direction and its wind speed can be determined. Due to the lack of LiDAR data the height of buildings and forests in the Park Forest/La North study area has been estimated. The custom developed ArcGIS extension "XTools Pro" has additionally been used to fulfill the slipstream calculation. Other factors that influence the results can be considered by the raster calculator tool at the end of the workflow. These factors include the soil type, terrain height, land cover, distance to power lines and the tolerance for slipstreams. Due to the fact that the study area has a rather flat topography, a second study area with much varied and complex topography was selected in addition to the first study area. However, the scenario for the mountainous study area in Villach, Austria was only theoretically elaborated, but not implemented. Additional research factors could not be implemented due to the fact that a computational fluid dynamic analysis would be necessary for a sufficiently high accuracy. These factors include the consideration of a minimum distance between small-scale wind power plants and an additional analysis for occurring wake and tunnel effects that can cause a lot of turbulences.

Table of Contents

List of Abbreviations

AuWiPot	*Austrian Wind Potential Analysis*
AWEA	*American Wind Energy Association*
dB	*Decibel* (10^{-1} *Bel)*
csv	*Comma separated value*
CUAS	*Carinthia University of Applied Sciences*
DEM	*Digital Elevation Model*
DOE	*U.S. Department of Energy*
DOQQ	*Digital Orthophoto Quarter Quadrangle*
DSM	*Digital Surface Model*
DTM	*Digital Terrain Model*
EIA	*U.S. Energy Information Administration*
ESRI	*Environmental Systems Research Institute*
EWEA	*European Wind Energy Association*
FEMA	*Federal Emergency Management Agency*
GIS	*Geographical Information System*
GPS	*Global Positioning System*
IEC	*International Electrotechnical Commission*
IMU	*Inertial Measurement Unit*
INFORSE	*International Network for Sustainable Energy*
JPEG	*Joint Photographic Experts Group*
kg	*Kilogram (*10^3 *gram)*
km	*Kilometer (*10^3 *meter)*
kW	*Kilowatt (*10^3 *watt)*
kWh	*Kilowatt-hour (*10^3 *watt-hour)*
LDEQ	*Louisiana Department of Environmental Quality*
LiDAR	*Light Detection and Range*
LSU	*Louisiana State University*
m	*Meter*
m^2	*Square meter*
m/s	*Meter per second*
MIT	*Massachusetts Institute of Technology*
MW	*Megawatt (*10^6 *Watt)*
NAD	*North American Datum*
NED	*National Elevation Dataset*
U.S.	*United States*
USGS	*U.S. Geological Survey*
USA	*United States of America*
UTM	*Universal Transverse Mercator*
V	*Volt*
VAC	*Volt Alternating Current*
VDC	*Volts in Direct Current*
W	*Watt*
WAsP	*Wind Atlas Analysis and Application Program*
WWEA	*World Wind Energy Association*
ZAMG	*Austrian Central Institute for Meteorology and Geodynamics*

1. Introduction

In this chapter the main content of the research is described. The first subchapter gives a specification of the motivation. The next two describes the goal and the hypothesis of this research. Chapter 1.4 gives a short overview over the used method of solution. In the last two subchapters the expected results and the structure of the work are delineated.

1.1. Motivation

Nowadays the world’s population is confronted with permanently increasing energy prices, caused by less available oil sources, conflicts in important oil delivering countries, such as Libya and the Iraq and disasters caused either by human failure or nature. The oil catastrophe in the Gulf of Mexico in April 2010, the nuclear catastrophe in Japan after an earthquake in March 2011 or the gas leakage on an production platform in the Northern Sea in March 2012 are only a few examples. Due to those events, many countries, such as Germany and Switzerland, are extending their capacity of regenerative energy to reduce the dependency on fossil and atomic energy sources. Therefore, private consumers who want to build their own renewable small-scale power plant are supported by their government. This research is focused on the siting of small-scale wind power plants.

Renewable energies reached an 8% amount of the total United States energy consumption in 2010. 11% of the renewable energy is taken by wind energy. Petroleum (37%), natural gas (25%) and coal (21%) are taking most of the total energy consumption, followed by 9% of nuclear electric power (EIA, 2012). In 2010 the United States ranks the second place in the worldwide total wind capacity with 40,180 MW, behind China with 44,733 MW. Thereof the capacity of installed small-scale wind power plants is amounted on 179,000 kW in the USA, followed by 166,000 kW in China and 42,970 kW in the United Kingdom (WWEA, 2012). With a yearly growth rate of 20% the wind energy sector offers a huge potential in the United States, resulting in low installation costs for a small-scale wind turbine. Depending on the type of the turbine, they amount to 4$ to 6$ per Watt in 2010 (Black et al., 2010). Nationwide initiatives like the U.S. Department of Energy's (DOE) wind program “Wind Powering America” are designed to accelerate the growth of wind power plants in the United States by providing breakdowns of wind resource potential, success stories, installed wind capacity, news and events for each state (DOE, 2012). Some of the states, such as Colorado, are providing a Wind for School program, where small-scale wind turbines are sponsored to supply schools with electricity (Colorado, 2012).

Motivated by the decreasing costs for small-scale turbine installations, the increasing energy prices and the high potential of the wind energy sector, this research aims to provide a discussion where suitable sites for different types of small-scale wind turbines are located. Therefore two study areas in a flat and a mountainous region have been chosen. The first study area is near Baton Rouge, Louisiana, USA and the second near Villach, Austria. Therefore it is anticipated that the results of this research will provide an improvement in the analysis of site potential to ensure better placement of these small-scale power plants.

1.2. Goal of the work

The goal of the research is to find the sites with the highest potential for different types of small-scale wind turbines in Park Forest/La North near Baton Rouge, Louisiana, USA. For future evaluation of the used methods, a mountainous study area near Villach, Austria will also be envisaged. To achieve the goal, a conceptual analysis model for the calculation of the wind speed and the slipstream of buildings, forests and topography will be developed and as an integrated calculation model in a GIS implemented. Therefore a Digital Elevation Model (DEM), wind data from the nearest weather station, geology data for determining appropriate soil, the distance to power lines and a land use data set to determine if the installation of a power plant is allowed will be used. Furthermore the model will be adaptable for more than one type of small-scale turbine, so that a result for each specific turbine can be generated.

1.3. Hypothesis

Through the usage of a specific GIS and custom developed extensions it is possible to estimate suitable installation sites for different types of small-scale wind power plants. Furthermore, the used GIS enables the calculation of slipstreams around specific objects like buildings, forests and topography.

1.4. Method of solution

In this chapter a brief overview of the influential parameters for the calculation of suitable sites for different small-scale wind power plants is discussed. The first parameter is the average wind speed that should at least exceed 2 m/s to get an acceptable performance for the smallest power plants. A parameter that cooperates with the wind speed is the wind direction. To be able to determine how often which wind speed from which direction occurs, a wind rose, as shown in figure 1, can be created. This one shows the deviation of the wind as seen from a weather station at the Ryan International Airport in Baton Rouge, Louisiana, USA. Therefore it results that wind is blowing from every direction, but the south exceeds the frequency of 5%. Also the colors represent the wind speed in a specific interval and the length of each color bar the duration.

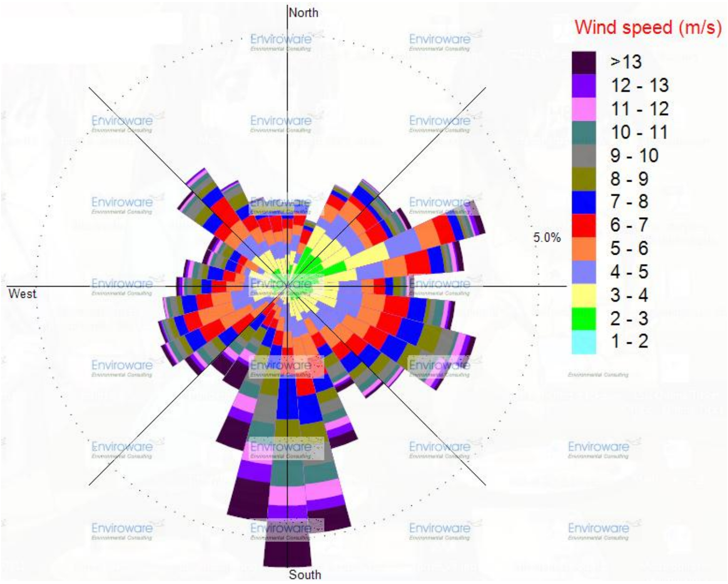


Figure 1: Baton Rouge Ryan International Airport wind rose (Enviroware, 2012)

The next important parameter to be able to show suitable sites for a specific wind turbine is the recognition of slipstreams. They appear next to obstacles, such as buildings, forests or topography and cause such high turbulences that the wind plant has to work with a damped performance. Two further important parameters are the maximum ground elevation and the maximum slope. Both may cause the local site to be inefficient due to suboptimal wind utilization. This happens most likely when the best site for a horizontal wind turbine has to be determined, because it has to be turned into the wind. A wind coming from beneath is normally no problem for a vertical axis turbine. Another important parameter that is considered in the calculation is the distance to an existing electricity grid, if the owner has the intention to feed the produced current in a power grid. Other important parameters are construction relevant criteria like the surface condition and the minimum area that is needed for the installation. By considering all of these criteria and the minimum requirements of a specific small-scale wind power turbine, it is possible to find its suitable sites in a study area.

1.5. Expected results

The expected results of the research are:

- Development of a conceptual GIS-based analysis model for locating suitable installation sites for specific small-scale wind power plants
- Evaluation of existing geodata regarding data quality and usability
- Implementation of the conceptual analysis model in ESRI's ArcMap for a study area in Park Forest/La North near Baton Rouge, Louisiana, USA
- Reflecting an evaluation and validation in a mountainous study area near Villach, Austria

1.6. Structure of the paper

The second chapter handles the theoretical background of the thesis. It includes the description of the terminology and gives examples of already existing solutions and initiatives in the field of small-scale wind power plants. Chapter three describes the methodology of the thesis, including an explanation of the used study areas, the problem definition, the used method of solution and implementation. Furthermore the used data is described and evaluated regarding data quality and usability. The chapter results in a summary to shortly review the process. The results of the research are shown and interpreted in chapter four. Chapter five includes a discussion of these results and chapter six handles a summary and a future outlook of the thesis. The seventh, eighth and ninth chapter include the references and either a table for used figures and tables in this paper.

2. Theoretical Background

In this chapter the basic theoretical knowledge that is needed for understanding the context of this paper is explained. Firstly the source of the wind and the relevant siting criteria for small-scale wind power plants to utilize it for energy generation is described. Then the different types of wind turbines are declared, showing the differences between vertical- and horizontal axis wind turbines. Furthermore an overview on Digital Elevation Models (DEM) and Light Detection and Ranging (LiDAR) data is given. The last chapter shows examples of already existing solutions and initiatives in the field of small-scale wind power plants.

2.1. Source of the Wind

In meteorology, the term Wind is defined as a natural and perceptible movement of air parallel to or along the ground. This movement occurs due to uneven heating of the Earth's atmosphere by the sun, causing a change in air pressure. When the air pressure in a specific area is higher than its standard sea-level pressure of 1013.2 millibar, it is called a high pressure or a low pressure area if it is lower. As shown in figure 2, low pressure areas are generated by heated air that rises to the upper atmosphere. When cooling down, the air sinks down in another area, causing a high pressure zone. On the Earth's surface the air moves from the high back to the low pressure area, causing a pressure gradient. The strength of the wind depends on the differences of the pressure areas. The greater the pressure difference of the locations is, the greater the pressure gradient will be and the stronger the wind.

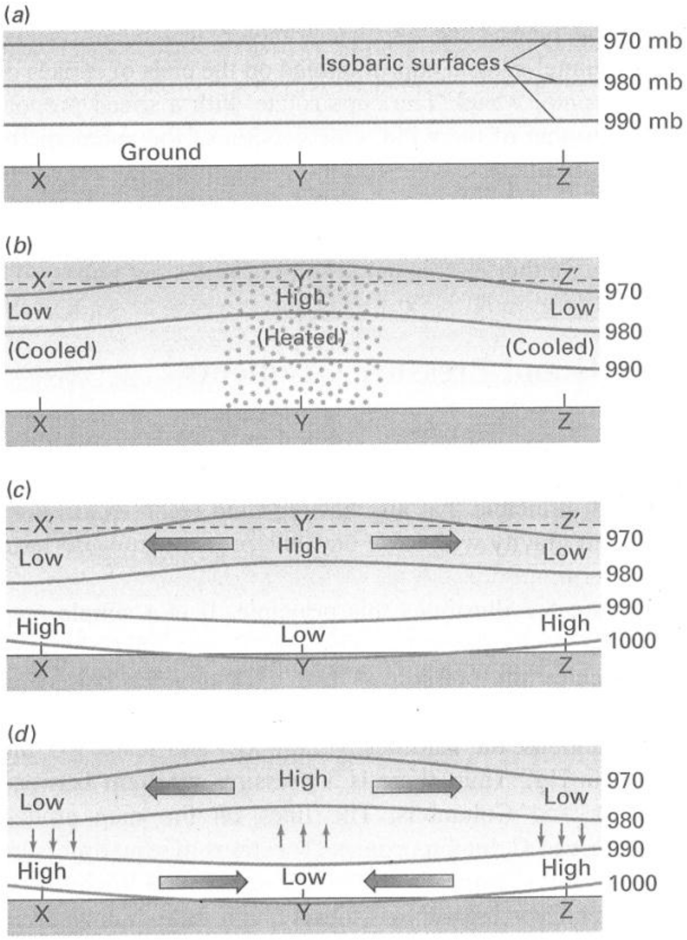


Figure 2: Atmospheric air circulation (Strahler et al., 2009)

Seen on a global scale wind is not a straight flowing force, but is influenced by the Coriolis Effect that is caused by Earth’s rotation. This force implies that an object in motion on the Earth’s surface always appears to be pulled sideways from its course. Therefore cyclones and anticyclones are generated. As seen in figure 3, an anticyclone is defined as a large-scale circulation of winds around a central region of high atmospheric pressure, clockwise in the Northern Hemisphere, counterclockwise in the Southern Hemisphere. A cyclone has a central region of low atmospheric pressure with counterclockwise circulation of the wind in the Northern and a clockwise in the Southern Hemisphere.

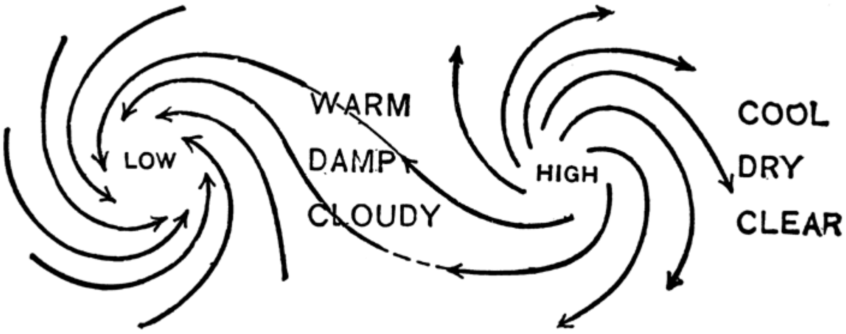


Figure 3: Cyclone and Anticyclone in the Northern Hemisphere (FCIT, 2012)

Beside the global influence of the Coriolis Effect, two local effects of wind generation are given. At coastal areas a sea breeze is created in the afternoon due to the faster heating of air above land mass than above sea. During night a land breeze transports the air from land back to the sea. At mountainous areas, Intense solar heating of mountain slopes generates a so called valley breeze during the day, bringing air from the valley to the mountain tops. At night a radiation cooling causes a downslope flow of cool air, causing a mountain breeze (Strahler et al., 2009). This descending air might be used for wind generation in mountain valleys.

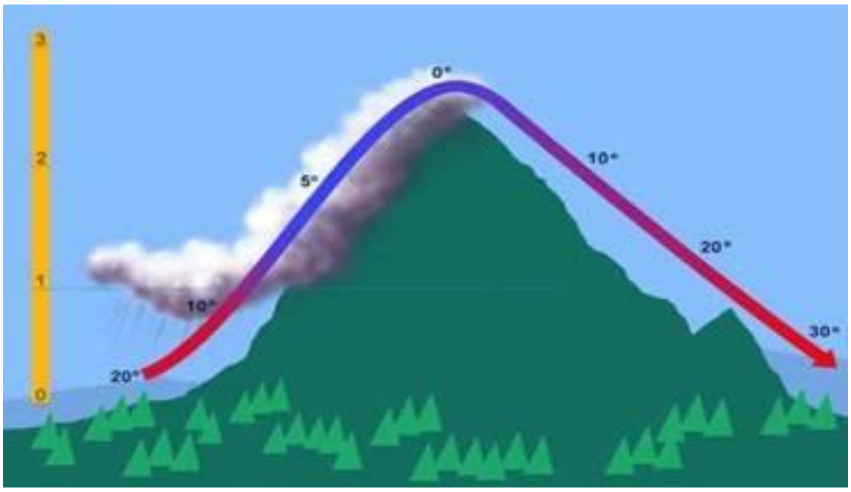
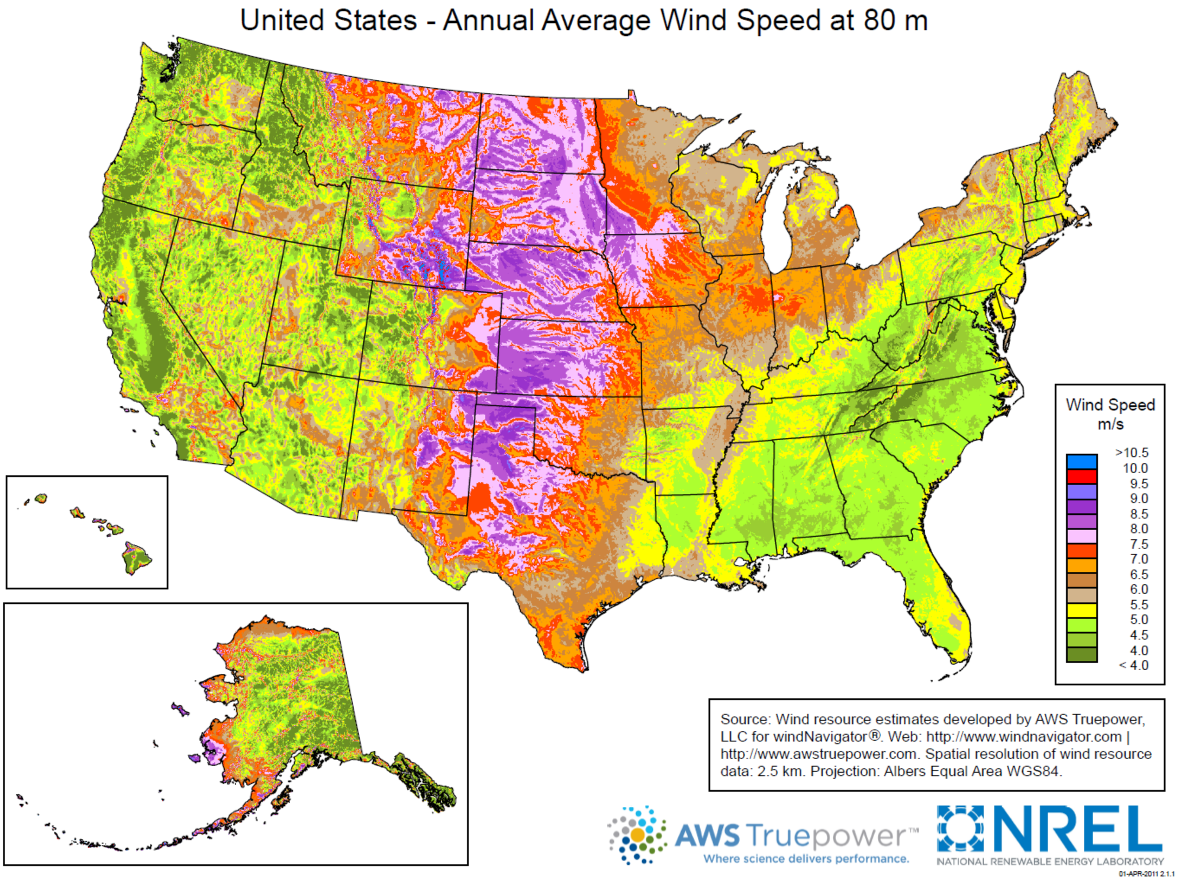


Figure 4: Evolution of foehn wind (XWeather, 2005)

As another wind pattern foehn wind occurs in alpine regions on the lee side of a mountain range. As it is shown in figure 4, on the luv side of the mountain range built-up warm, moist air rises and generates rain or snow due to its cooling. The dried air starts to sink on the lee side of the mountain range and blows as warm wind down to the valley (Levy, 2007).



Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

Figure 5: DOE wind map of the United States (DOE, 2012)

To be able to use the entire power of the wind, a siting process for wind turbines has to take place. The conditions for siting of a small-scale wind power plant differences fundamentally from those of a large one. The process with bigger, commercial plants normally follows three steps. Firstly a site with adequate wind conditions should be found. Therefore, wind maps can be used to find the best site, but a more specific wind evaluation for the chosen region should be created. Secondly the suitability for an installation on the chosen site has to be reviewed. As a third step the infrastructure and possibilities for a power connection should be investigated. As it is shown in figure 5, one of the best wind maps for the whole United States is provided by the U.S. Department of Energy. Those map offers the predicted annual wind speed in a height of 80 meters and has a resolution of 2.5 km, interpolated to a smaller scale (DOE, 2012). An onshore and offshore wind map for most of the western European countries is offered from the Danish research center Risø that is made from data provided by over 200 measurement stations on the European continent. It was developed by using computer based methods, such as Risø's Wind Atlas Analysis and Application Program (WAsP), where longtime measurements of all measurement stations has been cleared from local influences like orography, topography and obstacles, such as buildings or forests (Petersen et al., 1989).

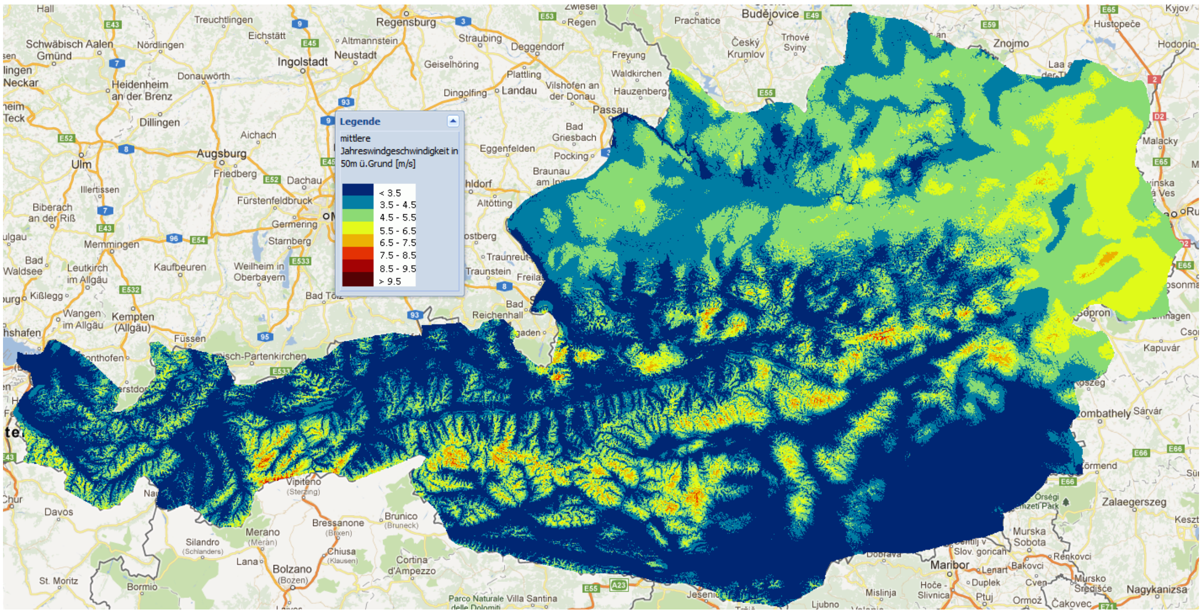


Figure 6: AuWiPot wind map of Austria (AuWiPot, 2011)

For Austria, an atlas from the Central Institute of Meteorology and Geodynamics (ZAMG) was the most accurate source for wind data until the end of 2011. To provide as accurate data as possible, the Austrian Wind Potential Analysis (AuWiPot) project targeted to develop an Austrian wind map with a resolution of 100 m x 100 m for different heights above the ground from 2009 to 2011 (AuWiPot, 2011). The result of this project is shown in figure 6. To be able to calculate the wind conditions on the chosen site, orography, topography and all obstacles have to be included in a numeric calculation. Additionally field measurements should be taken to evaluate the results of the calculation.

Due to the fact that small-scale wind power plants are most likely operated by private persons, small companies or small municipalities, the best wind conditions should be searched on their property in a much smaller scale. The possibility of making a site survey with an energy consulter would cost about 1,300 Euros in Austria. Therefore this option might be too expensive for most customers due to the chance of a negative survey. Another possibility would be the usage of the WAsP calculation program, but to be able to make a correct calculation expertise knowledge would be required. Also, the software would cost about 3,300 Euros, which exceeds the costs for other options by far.
Therefore a first reference point might be the observation of the nearest meteorological stations. Those data is public accessible over the Internet, such as on the website of the Austrian ZAMG, where over 200 measuring stations in Austria provide their data. The only thing that has to be considered is the height of the measurement that should correspond with the height of the wind turbine. Another option might be to make a measurement of the area with the help of a hand held anemometer. It should be considered that a short dated measurement with a cheap device has no significance. Therefore the purchase of an accurate anemometer with attached data logger is required to be able to make measurements on exactly the same position where the small wind turbine should be installed. Essential for the applicability of the measurements is the timeframe. It should at least amount a few weeks, so that it can be evaluated with the results of the nearest weather station. Better would be at least one year, so that the seasonal progression of the wind speed and a first annual average value can be estimated. An error might occur if the measured year has extremely low or

high wind compared to all other years, but this can be avoided if the measured data of the nearest weather stations are compared with the longtime mean value.
One of the most important facts for small-scale wind turbines is that each obstacle, such as a forest or building, should be avoided by keeping a specific horizontal or vertical distance to it. A rule of thumb says that each turbine should be at least in a distance of twenty times the height of the obstacle and should be the highest structure (Halbhuber, 2009).

2.2. Wind obstacles

If wind collides with an obstacle like a house or a forest, a turbulent area occurs behind this object. To be able to determine the length of those slipstreams, a fixed factor is used, which is multiplied to the height of each object. The amount of this value depends on the type of obstacle that is in the wind's way. It represents the rule of thumb that says that a specific distance and height behind an obstacle has to be secured, before building a wind power plant. Otherwise the small-scale wind power plant would be build inside turbulences, which prevent a continuous current production.

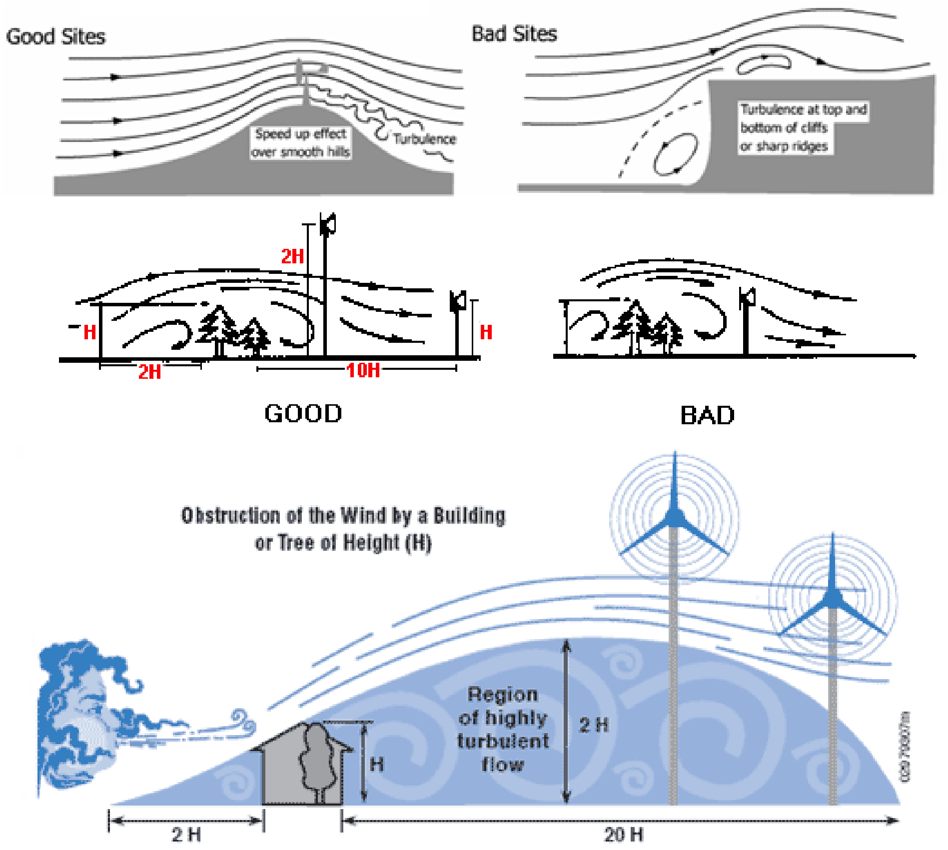


Image courtesy of the U.S. Department of Energy

Figure 7: Typical types of turbulences and their triggers

As it can be seen in figure 7, the first column of the first two rows shows a good site for small wind turbines, whereas the second column shows inappropriate sites. The good solutions show an example of a wind plant standing on top of the hill, which ensures a reliable energy production due to the fact that the wind is compressed on the windy side of the hill (Kyoto in the home, 2011). On the other hand a too steep cliff should be avoided due to occurring turbulences. The second example shows the minimum distance that should be kept from forests (INFORSE, 2010). It is at least 10 times the height of the trees. Therefore the factor is amounted with 12 when calculating the slipstreams for forests. The third row shows the same principle for single trees and buildings (The Worlds of David Darling, 2012). Hereby the factor is assumed to be 20 in the slipstream calculation. The wind speed does not affect the length of the affected turbulence region, but the strength of the occurring turbulences. More detailed information for slipstream calculation can be found in chapter 3.2.2.

2.3. Types of small-scale wind turbines

To give a better overview over the small-scale turbines market, a classification for different rotor types is given. A rotor has the function to transform kinetic energy of the wind to mechanic rotation energy and is therefore the central component of each wind power plant. Except of the small amount of special types, the market offered plants can be classified in four different rotor types.

As the first category, the propeller type rotor is the most widely spread construction form. It is a horizontal axis rotor that usually consists of three rotor blades. Its high level of efficiency is most likely the reason for its popularity. Newer rotors with optimized blade profile can reach a level of efficiency over 50%, what lies closely to the theoretical maximum value of 59%. This value was defined by Albert Betz in his Betzsches law from 1919. It says that the highest possible effective output of a wind power plant amounts 16/27 (nearly 60%) of the mechanical performance the wind can reach without breaking the rotor (Betz, 1926). The number of rotor blades in modern plants is mostly three, due to the high performance growth from one to two or even three blades. If adding a fourth blade, the growth would only lye at about two percent. Compared with the costs for a new blade and the increasing sound level, it would not be profitable.

The second category involves the Darrieus rotor that can be seen in the middle of figure 8. This vertical axis rotor was invented by Georges Darrieus, a French engineer, in 1925. A huge advantage of vertical wind turbines is that they don’t have to be tracked into the wind to work with a good performance. On the other side there are many disadvantages, like the maximum level of efficiency that amounts only 40%, ten percent less than a propeller type rotor. Furthermore is the production of the rotor blades more expensive, due to the needed geometric form and it can’t start running by itself. Therefore a motoric acceleration would be additionally necessary. Because of those disadvantages the Darrieus rotor is barely build anymore.

The third category includes the H-rotor, which can be seen on the right side of figure 8. It is a further development of the Darrieus rotor with three rotor blades that have the same distance from the rotor axis. Therefore it is easier and more often produced than its predecessor, but has the same low maximum level of efficiency.

The last category is the Savonius rotor that is shown on the left side of figure 8. It is the only vertical rotor that works with the principle of resistance, so that it has a maximum level of efficiency at about 20%. On the other side it runs practically noiseless, because the maximum speed of the rotor blades can’t exceed the wind speed. Therefore it can be used in sites where the level of efficiency is a less important factor than the noise level, like in urban areas. Furthermore small rotors of this type are used to give a start help for Darrieus or H-rotors.

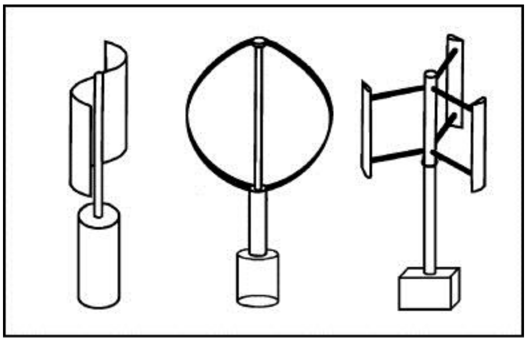


Figure 8: Savonius-, Darrieus- and H-rotor (Bernhoff et al., 2008)

Another important classification factor for small-scale wind power plants is the rotor diameter. This is shown in the two formulas below.

$$P_{mech} = c_p \frac{1}{2} \rho v_w^3 A$$

P_{mech} is the mechanical efficiency that amounts from Betz efficiency coefficient c_p, air density ρ, wind speed v_w and the rotor area A. Due to the fact that the most used horizontal axis wind turbine has a circular rotor area the next formula shows that the rotor diameter D is a squared variable in the calculation of the turbine's efficiency.

$$A = \frac{D^2 \pi}{4}$$

A standardized categorization of the different small-scale wind power plants that refers to the turbine's capacity is provided by the American Wind Energy Association (AWEA). A wind turbine with a capacity less than 0.9 kW is called micro wind, less than 10 kW residential, less than 20 kW commercial, between 20 and 100 kW upper commercial. Wind turbines that exceed a capacity of 100 kW are classified as large scale wind power plants (Halbhuber, 2009).

2.3.1. Examples for typical plants

In this chapter four commonly used wind turbines are discussed. At the beginning each type will be introduced. Furthermore a comparison of each other with the help of a table is presented.

Figure 9: Passaat wind turbine (The Spark, 2012) (Bright Green Energy, 2009)

As seen in figure 9, the first turbine is the Passaat model of the dutch company Fortis Wind Energy with a rated output of 1.4 kW. Fortis Wind Energy has produced the Passaat for more than 25 years and has sold 2,100 pieces worldwide. According to their own statement, they declare themselves as world market leader in small-scale wind power plants with a rated output of 1.4 to 10 kW. The turbine has three rotor blades and a horizontal axis rotor. The wind tracking is done with the help of a mounted wind vane that is able to turn the turbine automatically out of the wind in case of gales.

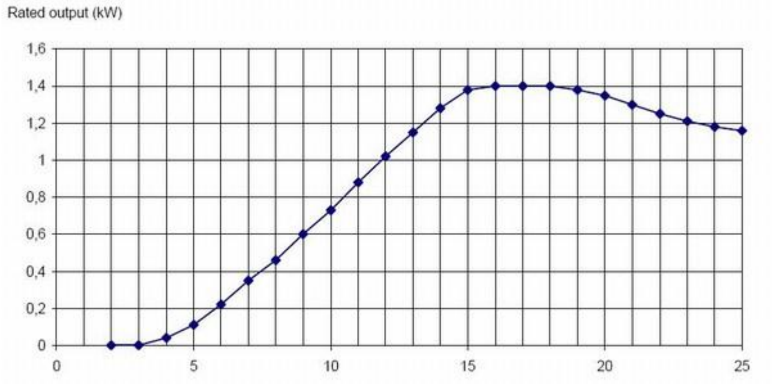


Figure 10: Passaat performance curve (Fortis Wind Energy, 2008)

The in figure 10 shown performance curve is resulting from this method of operation. The axis of abscissas shows the wind speed in m/s, the axis of ordinates stands for the rated output in kW. Therefore the most profitable site for this wind turbine should have a wind speed between 15 and 19 m/s. Additionally, this plant has a feeding inverter that enables the injection from the produced current directly into a low voltage grid.

Figure 11: Antaris wind turbine (Internationaler Marktplatz Windenergie, 2012)

As shown in figure 11, the second small-scale wind turbine is the Antaris model of the german company Braun Windturbinen GmbH with a rated output of 4.5 kW. Due to its yearly energy production it is already possible to cover the power consumption of an average household. Like the Passaat it has a horizontal axis rotor with three rotor blades and a mounted wind vane to be able to track the wind. Its most important feature is the implemented overspeed control that turns the rotor not sidewise out of the wind, but to the top into a helicopter position. Additionally a braking resistor with the performance of 6 kW is used to be able to slow the rotor when reaching an overspeed.

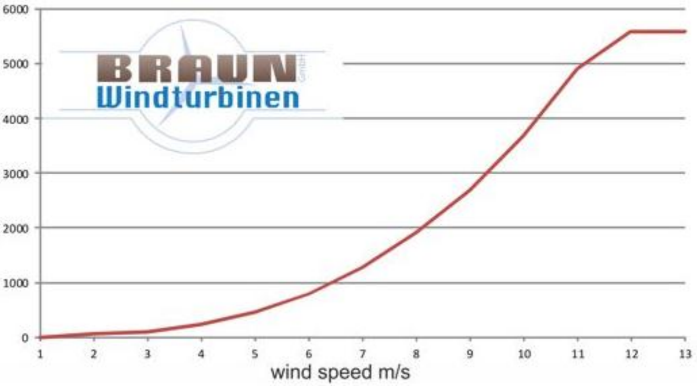
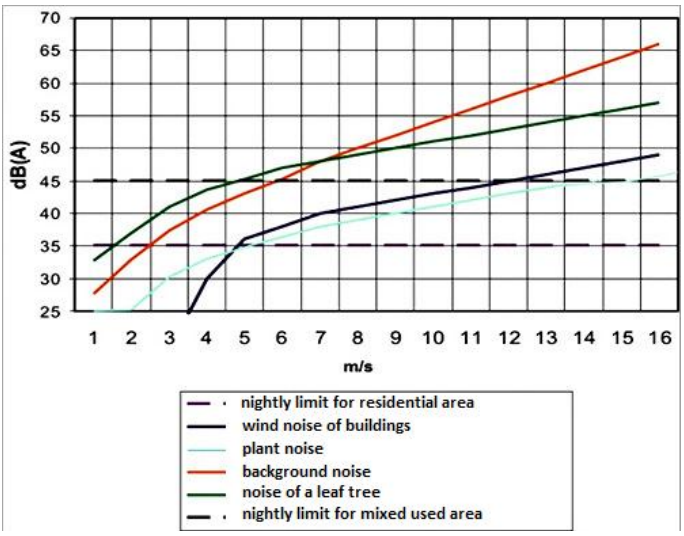


Figure 12: Antaris power curve (Braun Windturbinen GmbH, 2012)

As shown in figure 12, the performance curve exceeds the rated output to a maximum of 5.5 kW at 12 m/s wind speed. This should be taken with a pitch of salt, due to the producer's missing shut-down speed information and its low set rated output that is reached at 11 m/s with 4.5 kW.



0

Figure 13: Antaris noise level (Braun Windturbinen GmbH, 2012)

Figure 13 shows another special feature of this wind turbine. Due to bended rotor blade tops its noise level can be minimized, even under the noise level of buildings in the wind. The axis of abscissas shows the wind speed in m/s and the axis of ordinates shows the noise level in decibel (dB) of specific objects. This has also be taken with a pitch of salt due to a distance of 30 meters between the measuring device and the noise producing object and the fact that different types of houses and trees produce a different noise curve (Braun Windturbinen GmbH, 2012).

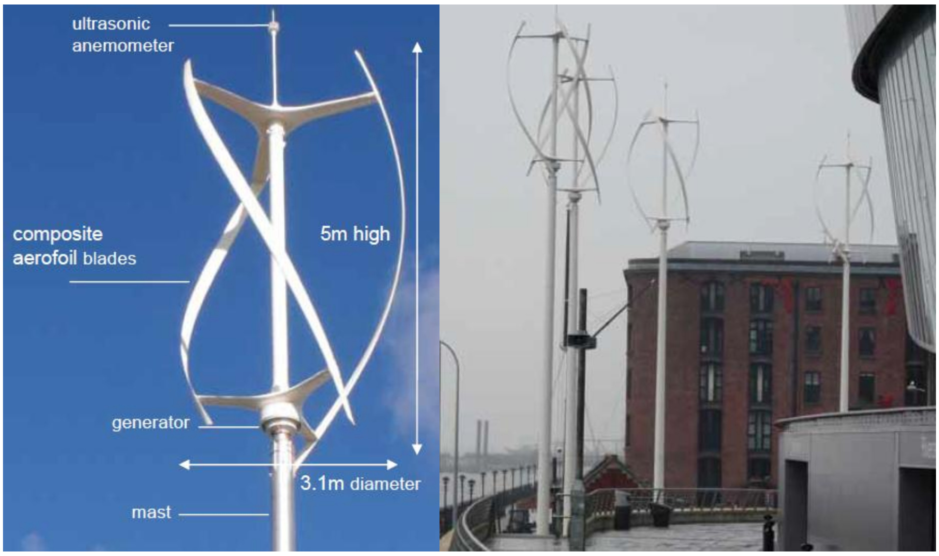


Figure 14: qr5 wind turbine (Minney et al., 2008)

As shown in figure 14, the third small-scale wind turbine is the qr5 of the British company quietrevolution ltd. that provides comprehensive information to this model on its website. It is a vertical axis turbine that uses the principles of an H-rotor and has a rated output of 6.2 kW. Different to the other two mentioned turbines it has three S-shaped rotor blades to provide a regular force distribution and less vibration. Also its rotor blades are bended to the rotor axis, so that the noise level can be minimized.

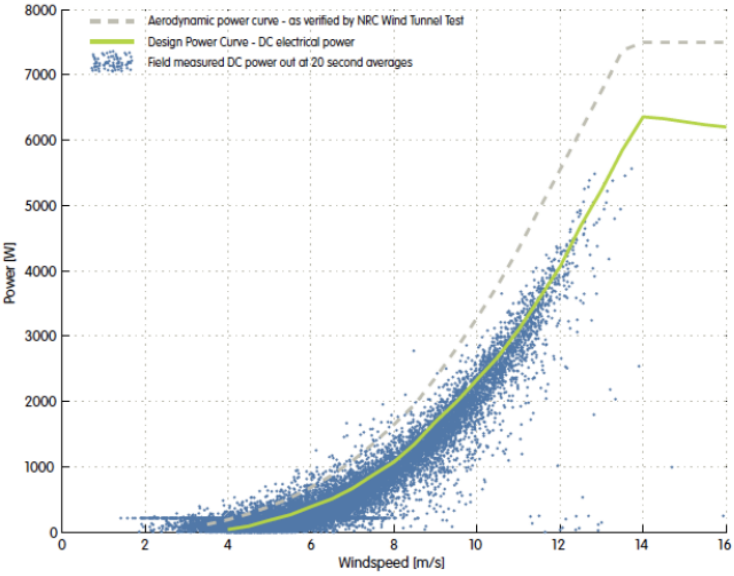


Figure 15: qr5 performance curve (Minney et al., 2008)

Beside other vertical axis turbines, the qr5 is able to control his speed and start-up time automatically by an anemometer that is placed on top of the turbine. The in figure 15 shown performance curve is resulting from this method of operation. The dotted line shows the aerodynamic performance measured in a wind tunnel, whereas the green curve is the predicted output. The blue points are registered 20 seconds average values from a field measurement.

Figure 16: qr5 spacing advantage (Minney et al., 2008)

Another advantage of this turbine are the 3.5, 6, 9 and 15 m high towers that are provided from the producer. As shown in figure 16, a distance of at least three rotor diameters should be provided between two vertical axis wind turbines. By using different heights, a closer rotor space can be achieved, so that more small-scale wind power plants can be placed on the same site (Minney et al., 2010).

Figure 17: PGE 20/35 wind turbine (JBS Solar and Wind, 2012)

In the strict sense of the International Energy Consortium’s (IEC) 61400-2 standard many models over 10 kW are not a small-scale turbine anymore, because they exceed a rotor area of 200 m², but the rated output of less than 100 kW is given. Despite its 290 m² rotor area the in figure 17 shown PGE 20/35 wind turbine of the Canadian company Energie PGE is discussed to ensure completeness (Tradekey, 2012). It has a rated output of 35 kW and is a horizontal axis turbine. Its three rotor blades can be regulated by a disc brake in case of overspeed. An essential difference of this plant is the process of wind tracking. This is ensured by the principle of a lee runner, what means that the rotor is tracked in the direction of the wind, behind the tower.

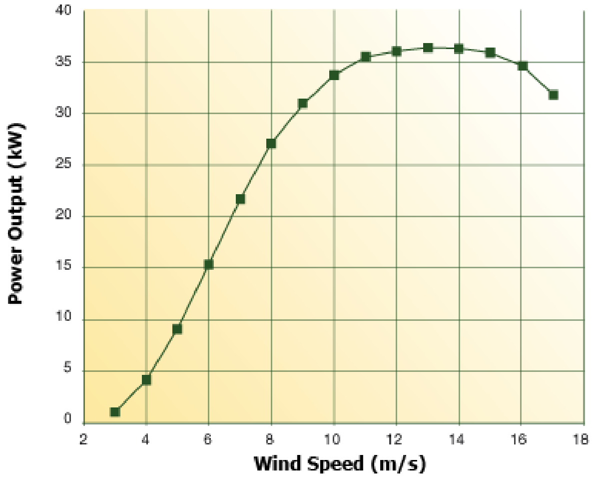


Figure 18: PGE 20/35 power curve (Halbhuber, 2009)

Figure 18 shows the power curve of the PGE 20/35 wind turbine. To reach the rated output a wind speed between 11 and 16 m/s should be prevailed. If the wind speed exceeds the border of 25 m/s the system stops the wind turbine by using implemented disc breaks to prevent damage on the plant (Halbhuber, 2009).

Table 1 shows a direct comparison of the discussed wind turbines. All listed values are taken from the producer's provided data. Not available specifications have been marked by a dash. These data has to be requested by the specific manufacturer in process of purchasing of a turbine.

Table 1: Comparison of four different small-scale wind turbines (Halbhuber, 2009)

	Passaat	**Antaris**	**Qr5**	**PGE 20/35**
Rotor diameter	312 cm	4.4 m	3.1 m	19.2 m
Rotor area	7.65 m²	15.21 m²	13.6 m²	290 m²
Rotor blades	3	3	3	3
Rated output	1.4 kW at 16 m/s	4.5 kW at 11 m/s	6.2 kW at 14 m/s	35 kW at 11 m/s
Start-up speed	2.5 m/s	1.8 m/s	4.5 m/s	3.0 m/s
Shut-down speed	-	-	16 m/s	25 m/s
Survival speed	-	-	55 m/s	52.5 m/s
Rated voltage	24/48 VDC	230/400 VAC	415/240 V	240/400/600 V
Yearly output	3,200 kWh at 6.0 m/s	-	9,000 kWh at 6.0 m/s	126,000 kWh at 5.0 m/s
Weight	70 kg	50 kg	450 kg	3.420 kg
Price	-	8,890 €	38,000 €	-

2.3.2. Areas of operation

The in chapter 2.2.1 mentioned small-scale wind power turbines have various areas of operation. The smaller Passaat is mainly used for battery charging than feeding the produced current in a low current grid. Therefore it is helpful in charging a battery during a windy time even when the battery’s power is needed beyond. Examples of use for that turbine are for example the charging of batteries on an advertising panel beside the street to ensure its illumination during the night or for an electrical fence on a ranch.

The Antaris and qr5 turbine are mainly used to feed its production in a low current grid, whereas it can be used by one or more households to ensure the current supply totally or just partly in order to save money. Both models have a very low noise pollution level, so that it does not matter if both turbines are used in urban areas. Only if more than one turbine should be used on one site, the qr5 has an advantage, due to its multiple sizes of towers, so that each turbine can work without any interference for the others.

Due to its high costs and size the PGE 20/35 turbine is mainly used in bigger customer clusters, such as small municipals, business enterprises or cooperative societies. Also, settlements without connection to the power grid, bigger American ranches or villages in Third World countries might profit from this type of wind turbine, due to the possibility to construct an insular grid for that specific area.

2.4. Digital Elevation Model (DEM)

A DEM is a constant two dimensional raster that provides information about the altitude of a specific surface, so that each raster cell includes one altitude value. DEMs can be created by using interpolation methods on point data. These points should hold accurate field measurements of the height of the terrain and occur in a consistent distance from each other. By modifying this distance the resolution of the resulting raster can be modified (Federal Emergency Management Agency, 2003). The term DEM is a hypernym for Digital Terrain Model (DTM) and Digital Surface Model (DSM). A DTM represents the surface without any objects, while a DSM includes the height of each object in the resulting raster.

2.5. Light Detection and Ranging (LiDAR)

LiDAR is an airborne laser system that is mounted in an airplane and consists of a high-precision Global Positioning System (GPS), an Inertial Measurement Unit (IMU) and a light-emitting scanning laser. It is collecting three dimensional coordinates of the earth’s surface by measuring the distance to the ground. This is determined by counting the time between the release of the laser beam and the return of its reflection to the laser system on the airplane. The IMU is recording the aircrafts orientation, gravitational forces and velocity by using a combination of gyroscopes and accelerometers while the GPS is determining the three dimensional position of the airplane. At the end of the LiDAR’s data record the data of all three devices is combined to generate a data point cloud. An advantage of this method is that it also works during nighttime or even on cloudy days, but therefore the accuracy of the output might be reduced (Federal Emergency Management Agency, 2003).

2.6. Related work

The increasing amount of investment in renewable energy, especially in the field of wind energy, reflects the increasing importance of alternative energy forms. This development gives private energy consumers the chance of purchasing an own small-scale turbine that should provide independence from the public energy grid. To be able to find the sites with the most wind potential, many projects have already been accomplished. To give an overview over those projects, this chapter deals with already existing solutions and worldwide initiatives that were founded to support customers and those who are interested in wind energy.

Nowadays nearly every industrial country provides a wind map of itself to be able to predict potentially good sites for wind farms. The in the United States most commonly used wind map is provided from the U.S. Department of Energy. For the most European countries the Danish research center Risø has generated a wind map from data provided by over 200 measurement stations. From these continental scale maps, smaller country based maps can be diverted and improved by local wind measurements. One example for this process is the Austrian wind atlas that has been developed by the AuWiPot project group from 2009 to 2011 (Austrian Wind Potential Analysis, 2011). A more precisely description about the named projects is given in chapter 2.1. However, those maps don’t provide an accurate representation of every potential site for a small-scale wind turbine and can only be used as point of reference. Therefore a survey on the specific site has to take place.

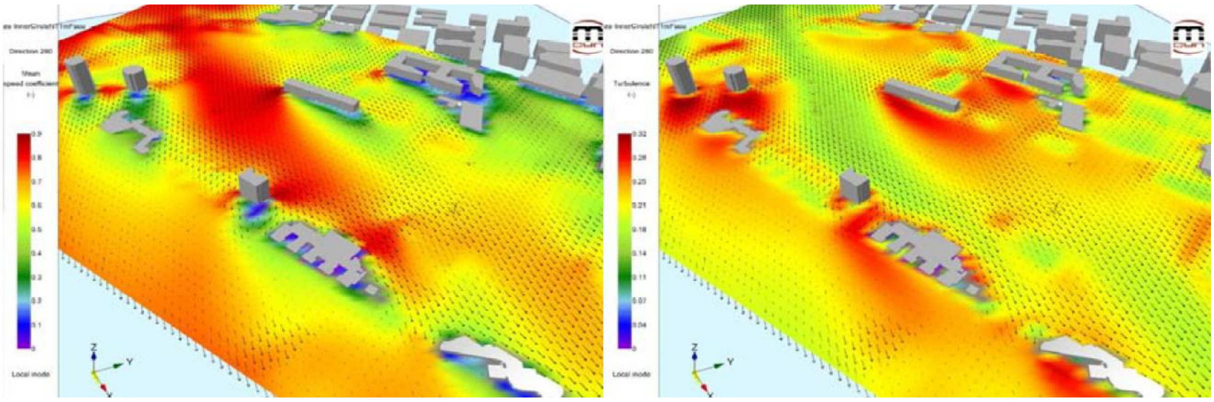


Figure 19: Wind speed induction and turbulence in the Full Breeze project (Full Breeze project team, 2010)

To provide as accurate data as possible, the Massachusetts Institute of Technology (MIT) has accomplished the project “Full Breeze”, showing the feasibility of small-scale wind power plants on their campus from 2009 to 2010. It was implemented by graduate students in cooperation with donors, members of industry and other wind power interested groups. They used advanced research tools such as computational fluid dynamic analysis as well as LiDAR remote sensing in a complex terrain environment to gain information about the turbulences and wind speed on the observation sites. As a result a colored interpolated surface of the campus is given, which shows the best places for two small-scale wind power plants in two different heights. In figure 19 the wind speed induction and turbulences of the study areas are shown. These are interim results from the computational fluid dynamic analysis that have been interpreted to find out how suitable the chosen sites are (Full Breeze project team, 2010). The research project WindArea of the University of Applied Sciences Frankfurt am Main is another project in that area. It targets on the development of an interactive web map that provides comprehensive wind speed data for the whole state of Hessen. The result should also show the suitability for different types of wind power plants with individual heights at any site. This is reached by an algorithmic calculation of 3D laser, wind speed and cadaster data of a specific region. As further results a strengthening of renewable energies in this region and the creation of a wind energy map for the public to look up the suitability for every type of wind power plant should be implemented (University of Applied Sciences Frankfurt am Main, 2012).

To be able to use such complex methods, high expertise knowledge has to be given. Therefore worldwide initiatives were founded, which have the function to promote wind energy with studies, market analysis and ads. Furthermore they are supporting people who are interested in wind turbines with financial and knowledge applied issues (Centre of Wind Energy Technology, 2005). The American Wind Energy Association (AWEA) is one of the biggest initiatives in the USA. It provides actual information about wind energy projects in their operating or development phase, companies that are working in the field of wind energy, the newest technological equipment and policy developments that are related to wind and other renewable energy developments. The goal of its over 2,400 members and advocates is to promote wind power growth through advocacy, communication and education (AWEA, 2012).

In Europe, the European Wind Energy Association (EWEA) has more than 700 members from nearly 60 countries, including manufacturers, component suppliers, research institutes, developers and electricity providers. Its vision is that wind energy should be the leading technology in covering the global energy supply based on indigenous, non-polluting and competitive renewable technologies. Therefore the initiative targets to facilitate national and international policies and initiatives that strengthen the development of global wind energy markets infrastructure and technology through effective communication and its engagement in the political decision-making process in order to achieve a more sustainable and cleaner energy future (EWEA, 2012).

The Austrian Wind Energy Association Interessensgemeinschaft Windkraft is promoting the newest information about wind energy in Austria. Besides their deployment of miscellaneous brochures about how wind power plants are working, they also provide a significant amount of statistical data of the country’s wind energy production. For potential purchaser of wind power plants, juridical issues for their state, success stories and studies about the newest available technologies are provided (Austrian Wind Energy Association, 2012).

3. Methodology

This chapter comprises the methodology of the thesis. The treated problem and its including challenges are defined in the first subchapter. Then the methodology of solving the defined problem is discussed, including the conceptual model, its implementation and workflows for data processing. Afterwards the study and evaluation areas are described, providing a reason why those have been selected. In the fourth subchapter a detailed description and evaluation of the used data is given. Afterwards the implementation of the conceptual model and its limitations are discussed. The last subchapter summarizes the whole section.

3.1. Problem Definition

As seen in the U.S. Department of Energy's wind map, Louisiana is one of the states with least onshore wind power potential at a height of 80 meters (DOE, 2012). Therefore, only a small amount of weather stations are measuring the wind speed and direction on the surface. One of the challenges was the acquisition, appropriate evaluation and processing of this data, so that the accuracy of the result is high. Another obstacle was the detection of possible slipstreams, due to the amount of buildings, forests and topography present in the study area. One of the biggest challenges was the development of a model that is able to give an accurate result for all different kinds of small-scale wind power plants. The main problem includes the preparation of highly accurate data and the development of a conceptual analysis model that involves all expected results.

3.2. Conceptual Modeling

In this subchapter, the methods of solution for the problems mentioned in chapter 3.1 are discussed. Therefore an Entity-Relationship- and a conceptual model is presented. It includes a solution of finding slipstreams of buildings, forests and topography with the help of empirical formulas and the factors that affect wind turbulences inside of them.

To be able to understand the coherences between the different components that are affected by the analysis, the Entity Relationship diagram shown in figure 20 has been designed.

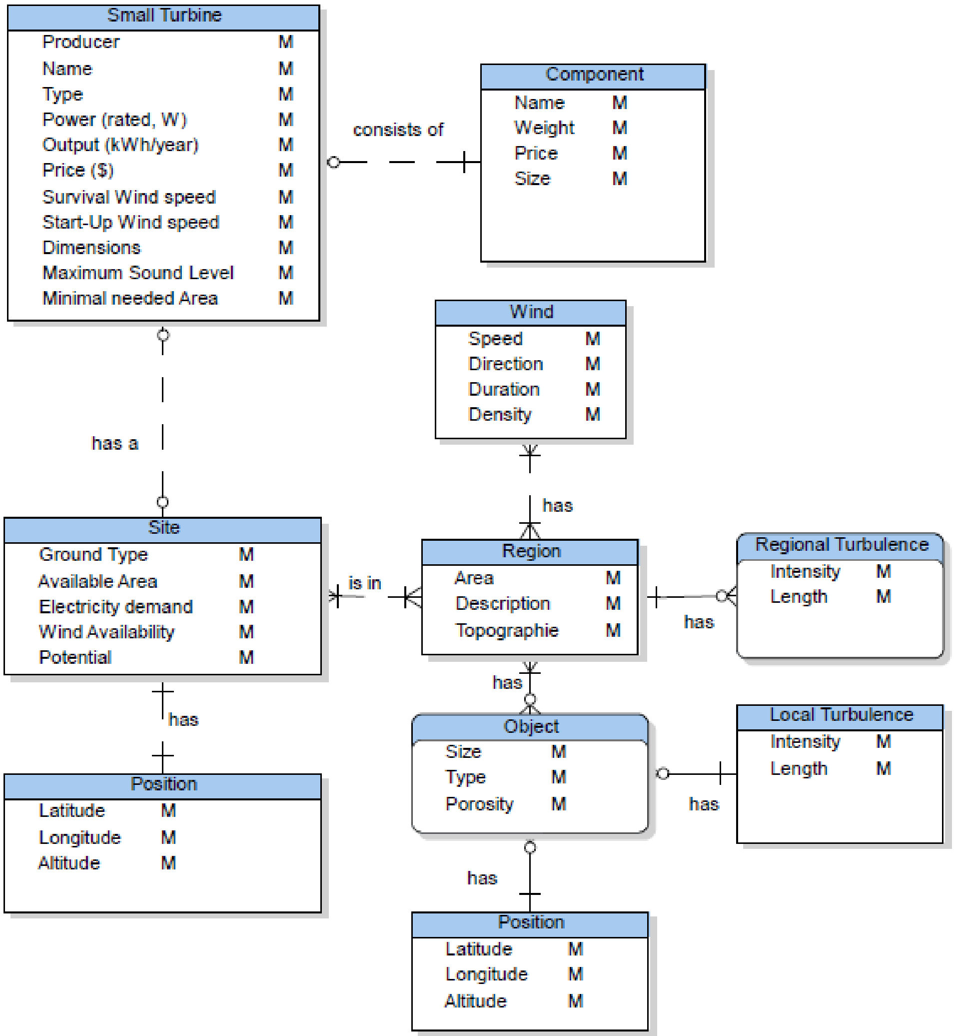


Figure 20: Entity Relationship diagram of the topic

The first entity in the upper left corner stands for the small-scale wind turbines. It varies in its producer, name, type, rated power, price and the actual output, measured in kWh per year. Also the survival and start-up wind speed, prices, sound levels, dimension and minimum needed area differs from turbine to turbine. The similarity of those small-scale wind power plants is that all of them consist of different kinds of different components with a specific weight, size, price and name and that all of them have at least one site when being operated. The site is specified by the type of ground that predominates, the available building area, wind availability, potential for a wind turbine and an electricity demand that has to be satisfied. It also has a fixed three dimensional position (latitude, longitude and altitude) and is part of a specific region. The region itself consists of an area with specific size, a description and topography. In the analysis the region is represented by the study area. Every region has its own wind pattern, regional turbulences and different local objects like buildings or forests. Each wind blows with a specific speed from a particular direction for a special amount of time with a specified density. Regional turbulences can be caused by topographic unevenness in the landscape. Examples for these turbulences are slipstreams that have a specific length and intensity behind the trigger. Local objects that are positioned in a specified region have a given three dimensional size (height, length, width), a specific porosity and different types, such as buildings or forests. Like the topographic unevenness in the landscape of a region, these objects are obstacles for the wind. They cause a local turbulence that has a specified size and intensity. Also each object has a unique three dimensional position (latitude, longitude and altitude) where the turbulences can be caused. As a next step the conceptual model has been developed. It includes the working steps that are necessary to fulfill the requirements of the analysis and evaluation. An overview of the conceptual model is shown in figure 21.

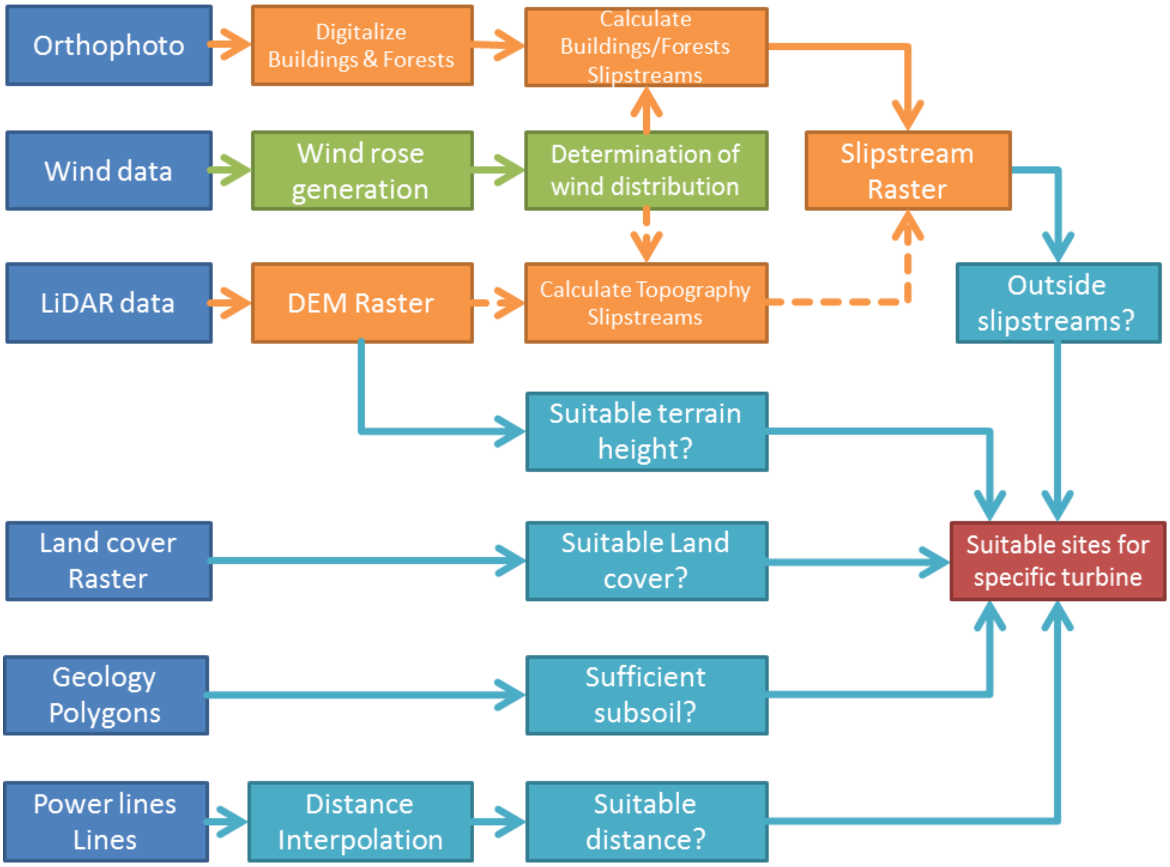


Figure 21: Overview of the conceptual model with the wind module in green, slipstream module in orange and the site suitability calculation in turquoise

3.2.1. Wind distribution

This chapter deals with the green colored wind module of figure 21. The wind data that was provided by the Louisiana Office of State Climatology was delivered as a comma separated value file, including an hourly measurement of wind from the year 2011 (LSU, 2012). To be able to evaluate the whole file at once the program WindRose PRO3 has been used. It enables the user to import a comma separated value file, processes and outputs it to a wind rose. The result of the Baton Rouge wind rose can be seen in figure 1, chapter 1.4 (Enviroware, 2012). With its help the wind distribution's direction, frequency and strength could be determined and forwarded to the slipstream calculation.

3.2.2. Slipstream calculation

This chapter deals with the orange colored module of the conceptual model overview shown in figure 21. The first row in figure 21 deals with the working steps of the orthophoto, building and forest datasets. With the help of the aerial picture both shapefiles could by digitized. Additionally the height of buildings and forests was added that can be determined by the already existing height data or via a field measurement using photogrammetric methods. These two vector datasets are also used in the slipstream calculation. The third row of the figure shows the type of processing for LiDAR or DEM data. In the case of the U.S. study area in Park Forest/La North, LiDAR data was not available, so that the step of converting it to DEM could not be accomplished. The DEM is used for the slipstream calculation and for determining the height of buildings and forests in the vector dataset for buildings and forests. The dotted components have not been implemented yet, but can be added for calculating slipstreams in a mountainous area. The gained knowledge of the wind rose is the central part in this analysis, as it is used in empirical formulas for making a circle of points that represent the slipstream around the building or forest polygon and around specific heights in the DEM. Those empirical formulas are stated as Equation 1 and have been used in the "Calculate Building/Forests slipstreams" step in row 1 of the figure.

$$x_{new} = x_{old} + \left(\left(\frac{height}{1°\ latitude\ in\ meters}\right) * f + \left(\sqrt{\frac{area}{\pi}}\right)\right) * \sin\left(wind\ direction * \frac{\pi}{180}\right)$$

$$y_{new} = y_{old} + \left(\left(\frac{height}{1°\ longitude\ in\ meters}\right) * f + \left(\sqrt{\frac{area}{\pi}}\right)\right) * \cos\left(wind\ direction * \frac{\pi}{180}\right)$$

Equation 1: Formulas for the slipstream calculation

Both formulas are using the principle of polar coordinate transformation. Therefore the new position of a point can be determined by adding a distance value to its x and y coordinates and multiplying it by the sinus or cosine of the specified azimuth angle. Due to the fact that the coordinates are given in latitude and longitude degrees, the height of the objects had to be transformed from meters to degrees. This has been accomplished by dividing it by the amount of meters that are equal to one degree on this position. In the Park Forest/La North study area one degree latitude amounts to 95,483.179047 m and longitude to 110,878.471206 m. Also an approximated radius of the building and forest polygons is added to support a more accurate result. It can be determined by dividing the area of a polygon threw Pi and taking the square root of the result. To be able to make a raster of the calculated points, they had to be transformed to polygons. For this purpose, the custom developed ArcGIS extension "XTools Pro" has been used. It includes more than 60 tools for vector spatial analysis, shape conversion, table management and 41 geo-processing tools that allow ArcGIS users to get to a new level of efficiency and performance. However, the only tool used for this analysis was the feature conversation tool "Make Polygons from Points" to be able to generate an appropriate dataset for slipstreams (Data East, 2011).

The factor f, which is multiplied by the transformed height, depends on the type of obstacle that is in the wind's way. It represents the rule of thumb that says that a specific distance and height behind an obstacle has to be adhered, before building a wind power plant. Otherwise the small-scale wind power plant would be build inside turbulences, which prevent a continuous current production. This principle is shown in chapter 2.2, where a value of 20 for buildings and 12 for forests has been chosen.

3.2.3. Site suitability calculation

The next steps after the slipstream calculation involve the turquoise colored steps in figure 21. The land cover, geology and power lines layer are simply clipped to the study area, so that only the important data for the analysis is remaining. Furthermore the distance from the power lines is determined by using a Line-Distance interpolation method. Those data layers, the DEM and the result of the slipstream calculation are then forwarded to a raster calculation, where each of them is filtered due to turbine specific requirements. For the slipstream raster the amount of tolerated slipstreams can be declared, so that not only places without slipstreams can be determined. The land cover raster has multiple terrain classes that specify what the area is used for. With this filter private property, national parks or water areas can be excluded. The geology filter determines on the exclusion of inappropriate terrain classes. Those categories include all soil types that are not appropriate for an installation of a small-scale wind power plant, like swamps or granite. The power line filter can determine the distance from the electricity grid, which is important for operators who want to inject the produced current. The last filter defines the suitable terrain height for the turbine, so that areas with cliffs or dips can be excluded. As a result only the suitable sites for a specific small-scale wind power plant are determined.

3.3. Study Area

As seen in figure 22 the study area chosen for the actual analysis is Park Forest/La North, a suburb of Baton Rouge. The left upper part shows a map of Louisiana's parishes, with the highlighted parish of Eastern Baton Rouge. On the right upper side of figure 22 the study area's location inside the East Baton Rouge parish is shown. The bottom part of the figure shows a more detailed visualization of Park Forest/La North. Baton Rouge is Louisiana's capital city with an area of 204.8 km². According to the U.S. Census Bureau the metropolitan area had 802,484 inhabitants in 2010 (U.S. Census Bureau, 2011). The area of Park Forest/La North has been chosen because of its mix of housing, industrial and rural areas.

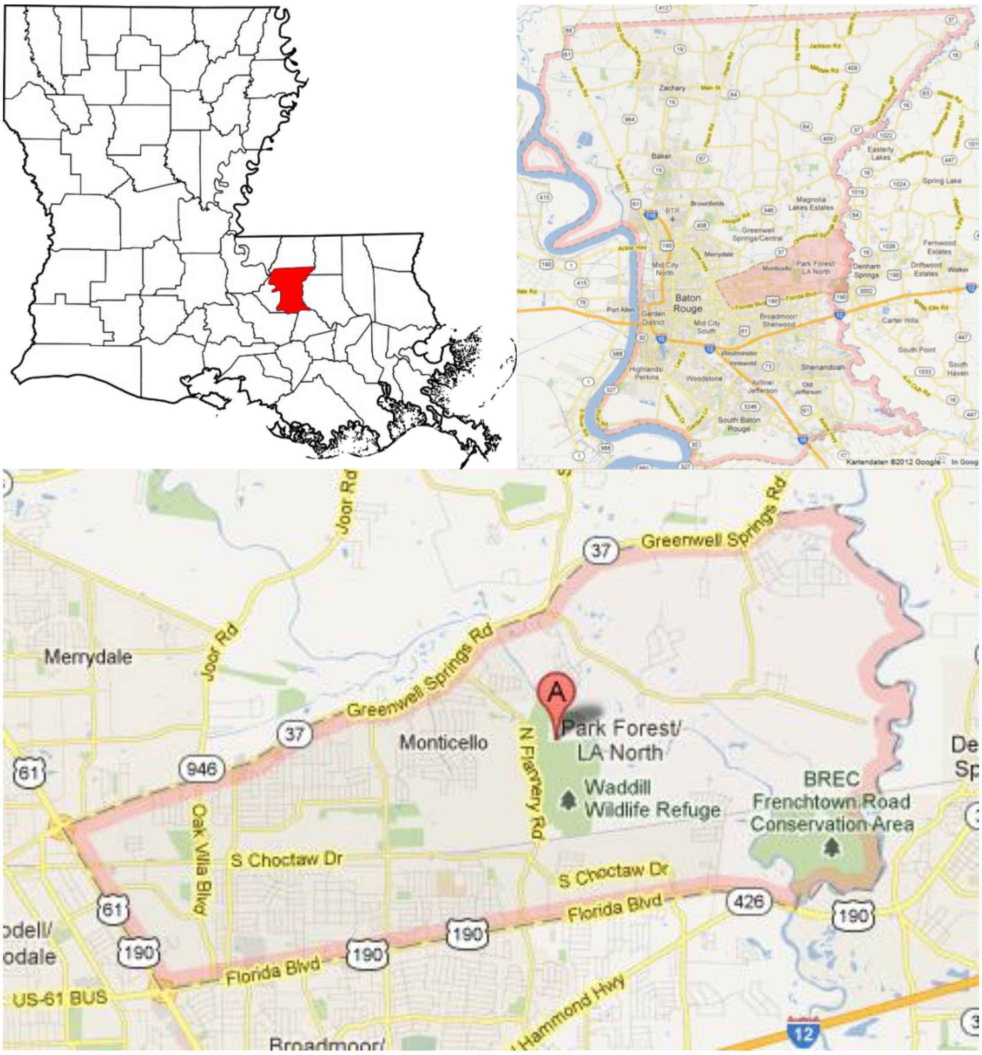


Figure 22: Louisiana's parishes and
East Baton Rouge Parish with Park Forest/La North study area

3.4. Data

This chapter discusses the data used in the research. The data section is divided into two categories. The first class represents the datasets that are needed to perform the analysis in a broad range of study areas. These datasets are shown in table 2. The second category is shown in table 3. It includes the data that was used for the actual application of the conceptual model in Park Forest/La North near Baton Rouge, Louisiana, USA. Each table in this chapter has four columns, whereas the first represents the name of the dataset that has either been taken from the metadata or was chosen by the author itself. The second and third columns are showing the file format and its extension. Column four involves the data format that can either be raster or vector. Vector data can either represent points, lines or polygons in the dataset.

Table 2: Necessary data to fulfill an analysis

Dataset Name	Format	Extension	Data Format
Buildings	Shapefile	.shp	Vector Polygon
Forests	Shapefile	.shp	Vector Polygon
LiDAR data	Comma Separated Value	.csv	Vector Point
Geology layer	Shapefile	.shp	Vector Polygon
Landcover layer	-	-	Raster
Orthophoto	-	-	Raster
Powerlines	Shapefile	.shp	Vector Line
Roads	Shapefile	.shp	Vector Line
Wind_Measurements	Comma Separated Value	.csv	-

Table 2 gives a listing of data that is needed to perform the analysis for a broad range of study areas, including the envisaged in Villach, Austria and Park Forest/La North near Baton Rouge, Louisiana, USA. The buildings and forests datasets are two custom-generated shapefiles that have to be created by digitizing from the orthophoto. The geology, powerlines and roads layers should be like those used in the analysis for Park Forest/La North and described in the next paragraph. That means that those three layers should at least be saved as a shape file, so that the geology layer includes polygons and the others lines with specific attributes. The landcover layer and the orthophoto should be in raster format, so that no extra conversion is necessary. The wind measurements of the study areas' nearest weather station should be stored in a comma separated value file. This file should contain a one year hourly measurement of wind speed and direction, so that further calculations like the determination of a yearly average and the creation of a wind rose are possible. If the mentioned data is used, the model should be similarly applicable to a mountainous study area in Villach, Austria. Wind data for the evaluation study area might be provided by the Sensors4All project of the Carinthia University of Applied Sciences. The project team has built a micro sensor network in the region in and around of Villach and collects data since July 2011 (Sparkling Science, 2011).

Table 3: Datasets used for the Baton Rouge analysis

Dataset Name	Format	Extension	Data Format
Baton Rouge wind data	CSV	.csv	-
Buildings	Shapefile	.shp	Vector Polygon
Forests	Shapefile	.shp	Vector Polygon
dem24k_ldeq_2004	DEM	.tif	Raster
geology_NWRC_1998	Shapefile	.shp	Vector Polygon
Lancovi200l	GeoTIFF	.tif	Raster
Orthophoto Park Forest/La North	JPEG 2000	.jp2	Raster
Powerlines	Shapefile	.shp	Vector Line
tiger_la_roads_CENSUS_2006	Shapefile	.shp	Vector Line

The first dataset listed in table 3 is the Baton Rouge wind data. It is a comma separated value file that involves hourly wind measurements of the study areas' nearest weather station at the Baton Rouge Ryan International Airport from 2011. The data has been received from the Louisiana Office of State Climatology, which provides 15 measurement stations on the surface of Louisiana (LSU, 2012).

The next two datasets in table 3 represent the buildings and forests in the study area. The shapefiles were created to store polygons with a height attribute. Also their area is stored to be able to make a more accurate calculation of the slipstreams, as it is defined in chapter 3.2. If LiDAR data is used in the analysis, the height can be determined by a DEM that can be created through a conversion of the LiDAR data.

The fourth dataset in table 3 is a Louisiana Digital Elevation Dataset that was derived from the U.S. Geological Survey (USGS) National Elevation Dataset (NED) by the Louisiana Department of Environmental Quality (LDEQ) (USGS, 2006) (LDEQ, 2012). Its data has been projected to Universal Transverse Mercator (UTM) Zone 15, North American Datum of 1983 (NAD 83). Also the vertical units have been changed from meters to feet. The USGS NED is a seamless mosaic of best-available elevation data. For this dataset the 7.5-minute elevation data for the conterminous United States are the primary initial source data (USGS, 2012). It is provided by the Louisiana Oil Spill Coordinator's Office (LOSCO).

The fifth dataset includes the geology of Louisiana from 1998, projected in UTM on the NAD 83. It was published by the USGS' Biological Resource division and is provided now by LOSCO (USGS, 2012). The dataset contains vector polygon information that includes base categories and characteristics of geological features.

Dataset six is a GeoTIFF land cover raster layer that was created by the National Center for Earth Resources Observation and Science of the USGS (USGS, 2010). It contains a conterminous land cover of the whole United States from 2002 with a resolution of 200 meters. The dataset was produced for the 2002 National Land Cover Dataset, based on Landsat Thematic Mapper satellite data. A clip of this dataset to the area of Louisiana has been used for the analysis.

The seventh dataset is a standard color infrared USGS digital orthophoto Quarter quadrangle (DOQQ) of the study area Park Forest/La North near Baton Rouge, Louisiana. A DOQQ is a raster image, with displacement caused by sensor orientation and terrain relief has been removed. It is projected in UTM on NAD 83 and has a geographic extent equivalent to a quarter of a 7.5 minute map (3.75 minutes of latitude and longitude) (USGS, 2012).

The eighth dataset represents Louisiana's powerlines in vector format. It has been created by LOSCO in 1999 and is also projected in UTM on the NAD 83 (LOSCO, 2012). The data is provided by the Louisiana Statewide GIS Atlas of the Louisiana State University (LSU, 2012). The attributes give information on the length of the lines and their type.

Finally, the ninth dataset is an extract of selected geographic and cartographic information from the Census TIGER database (U.S. Census Bureau, 2011). It includes all streets of Louisiana from 2006. The attributes involve the name, type and length of every street. The dataset has been clipped to the size of the study area, so that the handling of unnecessary data has been avoided.

3.5. Implementation

This chapter deals with the visualization of the chosen datasets in the study area of Park Forest/La North and the interim steps of the slipstream calculation. Also a comparison of the calculation's results and the reality is given. The implementation has been completed in ESRI's ArcMap with the help of its Model Builder. Therefore a wide range of tools have been used to manipulate the data.

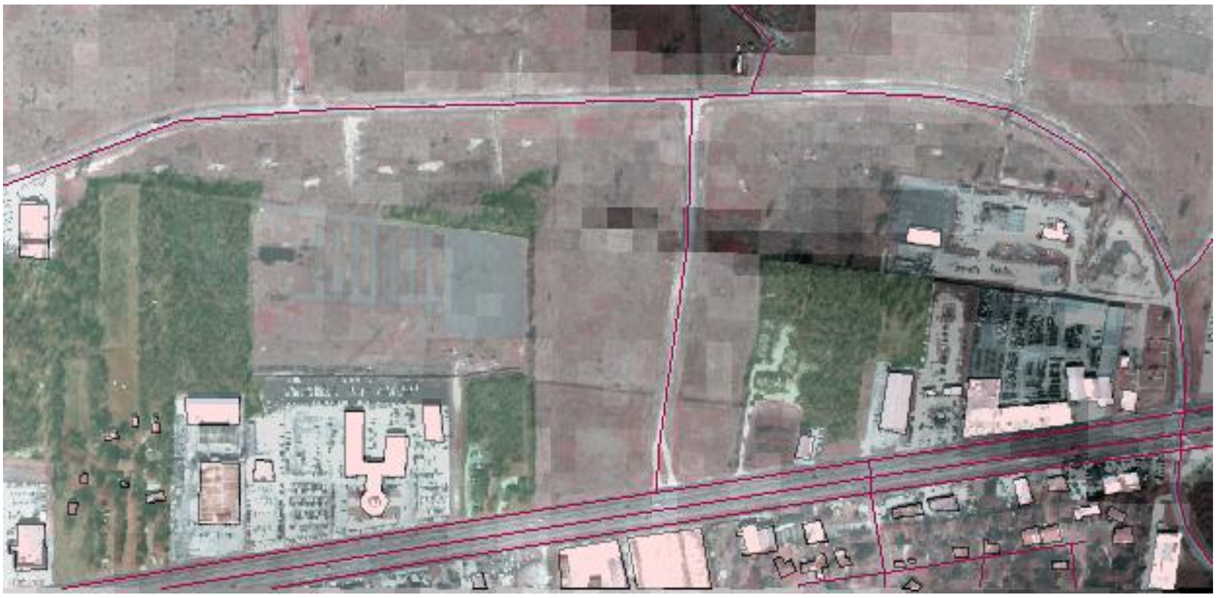


Figure 23: ArcMap-visualization of the datasets used in the US study area

Figure 23 shows the visualization of the data when loading them into ArcGIS. The data has already been clipped to the study area that is represented by the orthophoto. The roads dataset is shown as violet lines. Therefore it can be seen that a main street runs through the study area. The DEM layer can be seen behind the partial transparent orthophoto. The from white to black reaching colors range shows an altitude difference in the study area from only five meters.

The buildings and forests shapefiles have already been filled with the necessary data. Those are shown as green and beige polygons in the study area.

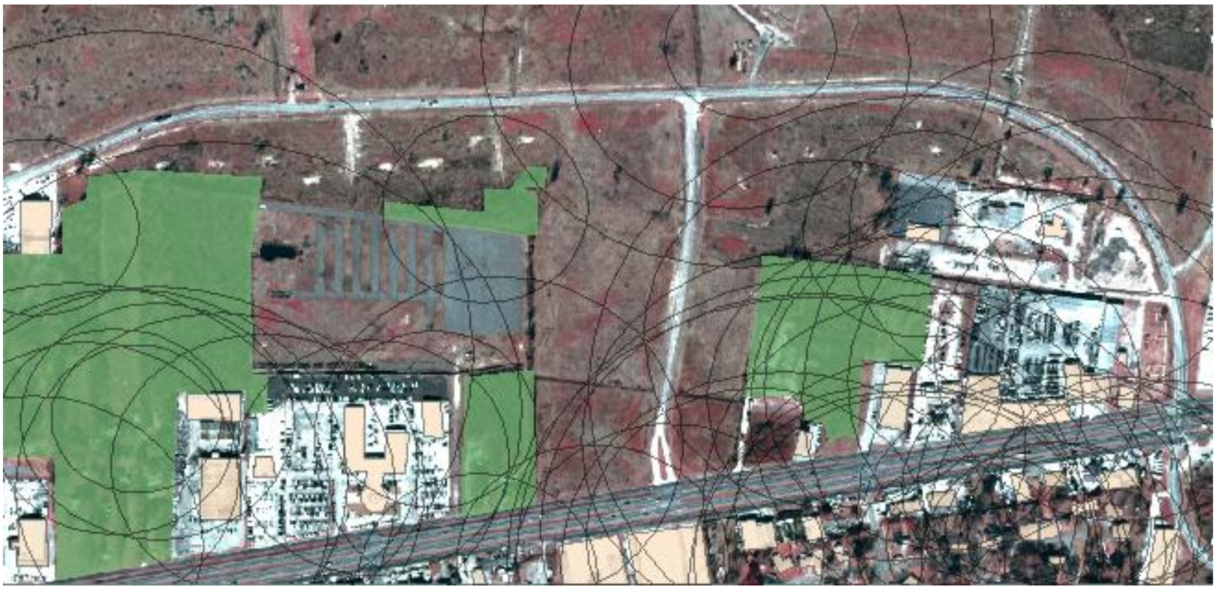


Figure 24: Result of the slipstream calculation

As shown in figure 24 the slipstream calculation results in a set of circles in this study area. This is because the uniform distribution of the wind direction’s frequency is less than 5% in every direction, as it can be seen in the wind rose in chapter 1.4. Therefore all directions were equally affected in the slipstream formulas that are mentioned in chapter 3.2. However, this is not the general case. It may be possible that the wind blows most of the time from only one or two directions or that only those directions with a specific frequency are chosen for the analysis. But this has not been considered in the conceptual model developed in the thesis.

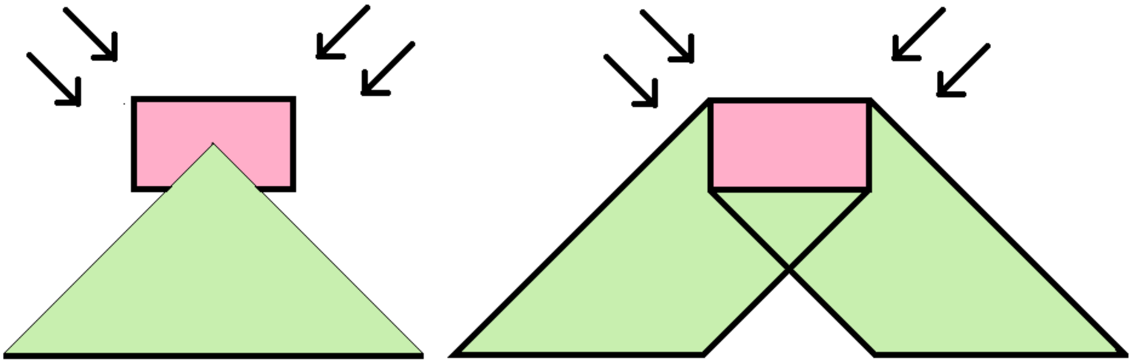


Figure 25: Comparison of the slipstreams from the model’s result on the left and the reality on the right

In figure 25 the boundaries of the model’s slipstream calculation are shown. The arrows represent the wind that blows from the left and upper corner. The red rectangle is a simplified description of a building that is an obstacle for the wind. Therefore the green drawn slipstreams occur. As it is shown on the left-hand side of the figure, the developed model would react in the way that points are shifted from the center with a distance of 20 times the height of the building to the specific directions. Compared to the “how it should be” example on the right-hand side of figure 25, it can be shown that the result shown in the left side of the figure is incorrect.

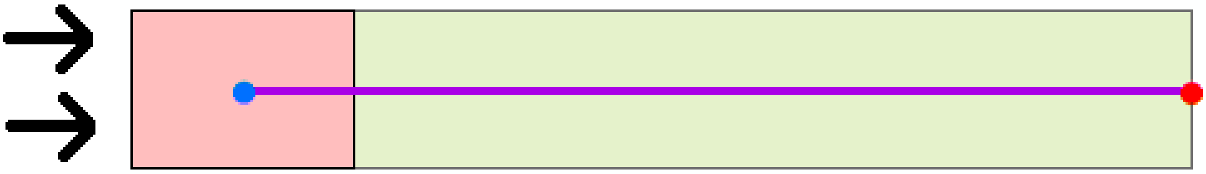


Figure 26: Approaching slipstream calculation from one wind direction

Therefore it might be a possible approach to use the method shown in figure 26. Hereby the length of the slipstream has been calculated with the help of the in chapter 3.2.2 mentioned formulas. Afterwards the center of the building and the resulting point has been connecting by the in figure 26 shown purple line. As a last step a buffer of half the width of the polygon has been generated. It can be seen as green rectangle in the figure.

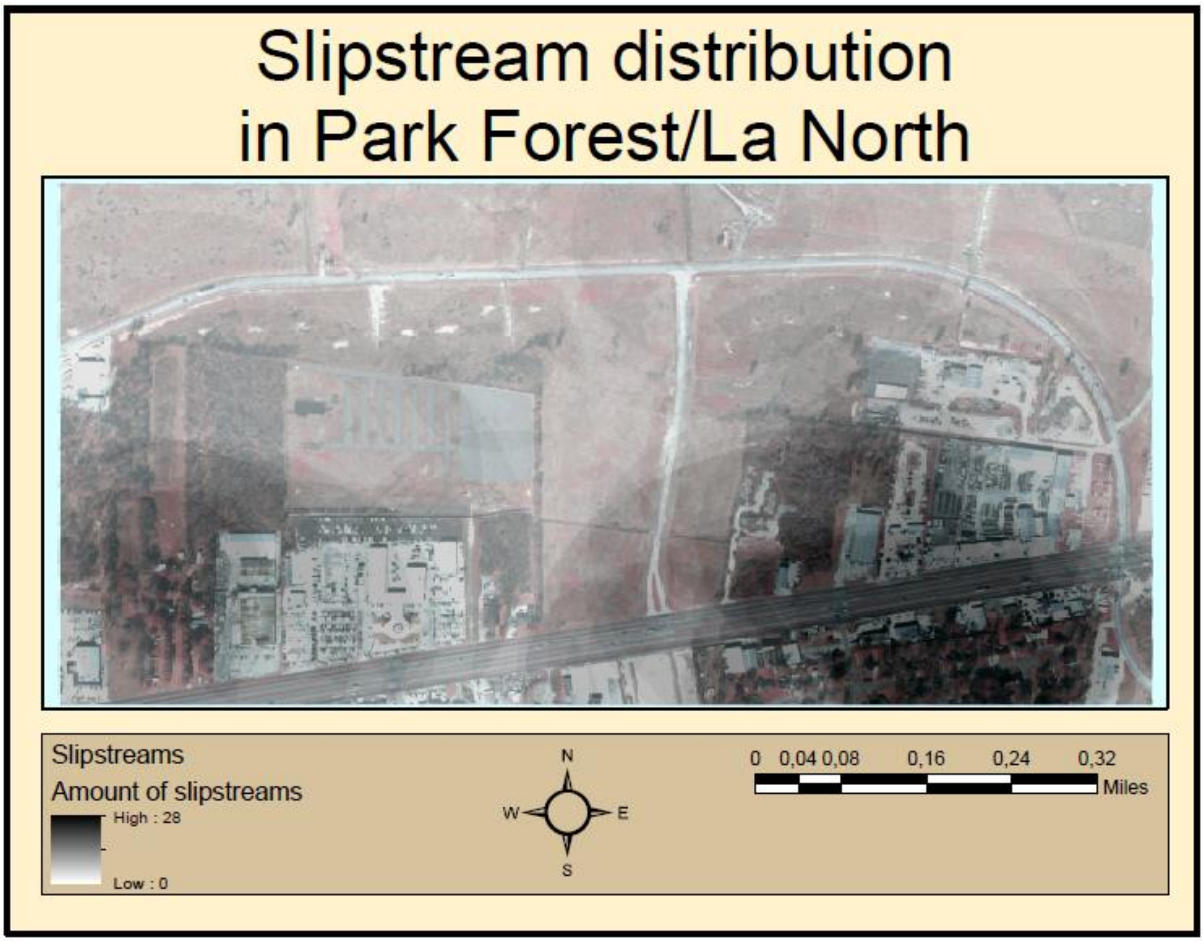


Figure 27: Map of the slipstream distribution in Park Forest/La North

For better understanding of the calculations results, the map in figure 27 shows the amount of overlapping slipstreams as a raster on top of the study area. The darker the area, the more slipstreams can occur. The lowest amount of slipstreams can be found in the upper half of the study area, whereas the lower half amounts up to 28 overlapping slipstreams.

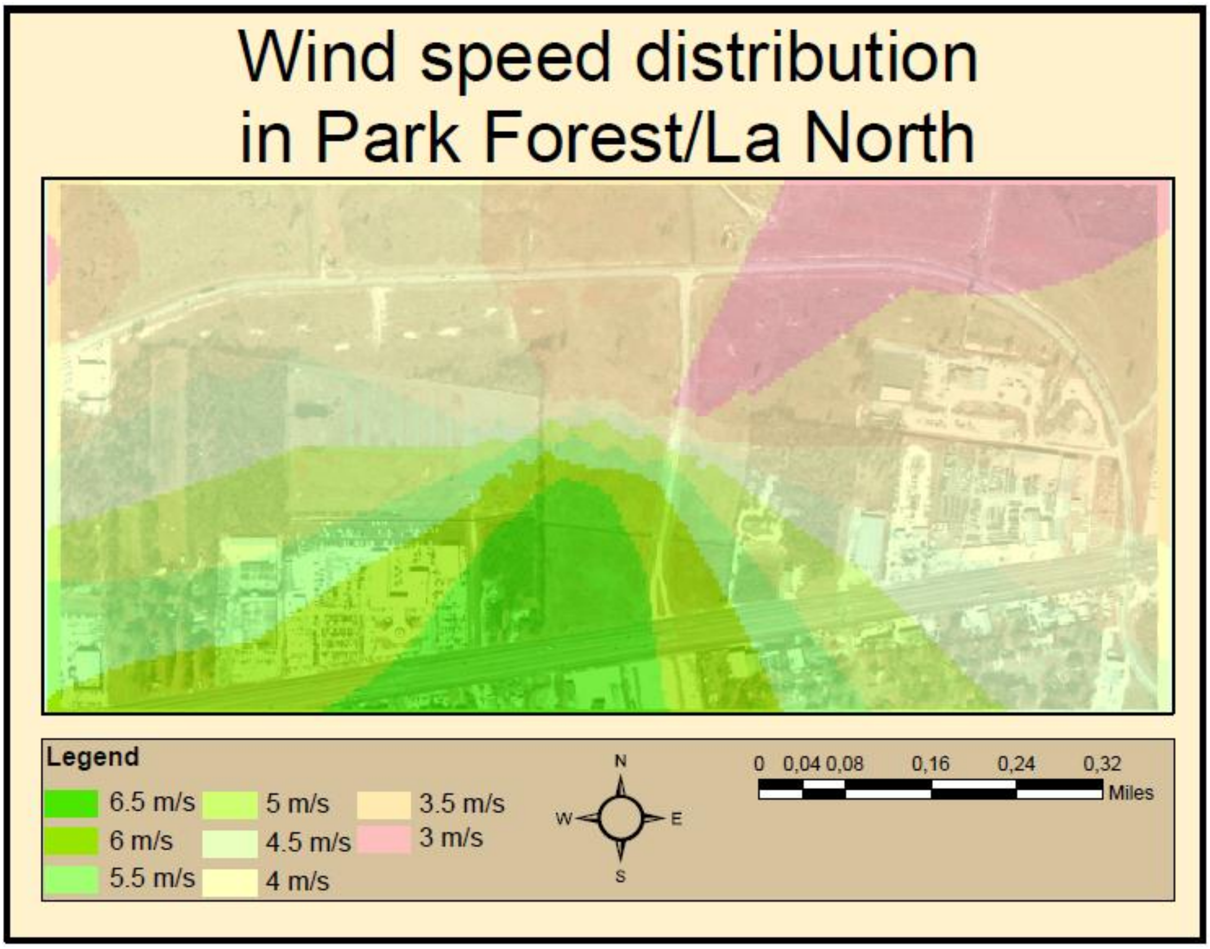


Figure 28: Map of the wind speed distribution in Park Forest/La North

To be able to interpret the results of the analysis map with the average wind speed in the study area has been created and is shown in figure 28. It includes classified average wind speed distributions from 2011 that has been taken from the wind data of the Baton Rouge measurement station. Therefore a wind between 3 m/s (reddish) to 6.5 m/s (greenish) is given in this study area, whereas the lower half has faster winds than the upper.

3.6. Summary

The first subchapter in chapter 3 defined the multiple problems and challenges of the thesis. Subchapter 2 includes the description of the Entity Relationship- and conceptual model of the analysis and reflects the reasons why this approach has been chosen. Also a description of slipstream characteristics and the ArcGIS extension "XTools Pro" is discussed. Afterwards the study area in Park Forest/La North, near Baton Rouge, Louisiana, USA and why it has been chosen is described. After the definition of the study area the datasets that are required for the analysis and evaluation of the model are described. The fifth subchapter deals with the results of the slipstream calculation and the resulting boundaries that are reached with the implementation of this conceptual model.

4. Results and Interpretation

This chapter presents and discusses the results of the research. First the results of the analysis of Park Forest/La North in Baton Rouge, Louisiana, USA are described. Therefore the performance curves of the four presented small-scale wind power plants are interpreted with the results of the analysis. Afterwards the expected results of the study area in Villach, Austria are introduced and compared to the results of Park Forest/La North.

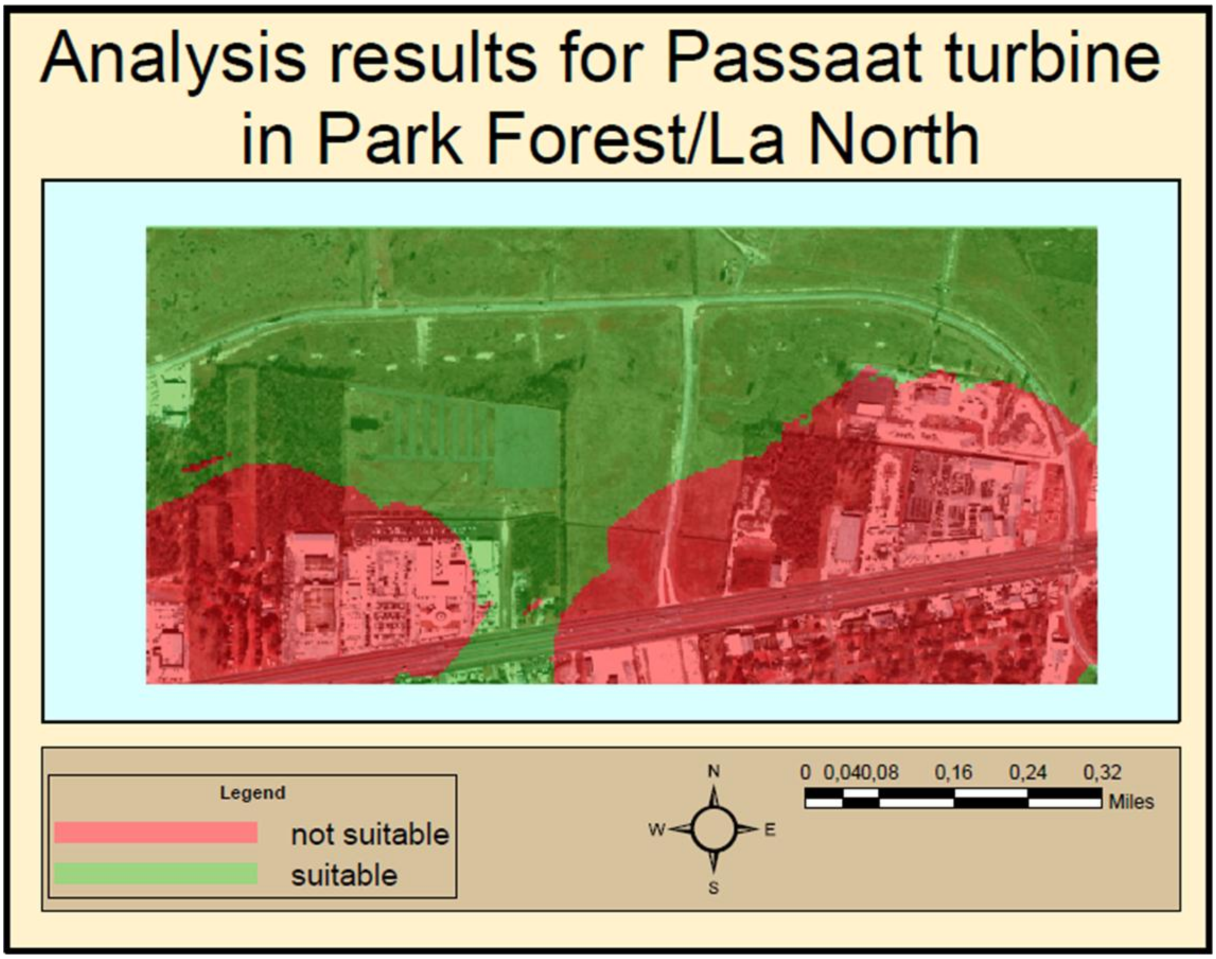


Figure 29: Result of the raster calculation filter for the Passaat wind turbine

In figure 29 the calculated results for the Park Forest/La North study area, based on the implemented conceptual model, are shown. The analysis was made for the Passaat wind turbine that is described in chapter 2.2.1. It requires a start-up wind speed of 2.5 m/s and has a rated output of 1.4 kW at 16 m/s. Therefore the filters were set to a minimum of 2.5 m/s wind with a slipstream tolerance of 5. The tolerance defines how many slipstreams are allowed to overlap in the specific area. The height difference in the study area's terrain is only 3 meters, so that this filter has not been activated. All existing types of land cover are suitable for this study area, because there are no water surfaces or national parks. The geology filter has nothing filtered, due to the fact that only Loess and Alluvium are present. Both Loess and Alluvium are suitable for building a small-scale wind power plant. Power lines have nearly the same distance in the whole study area, so that the power line filter carries no weight.

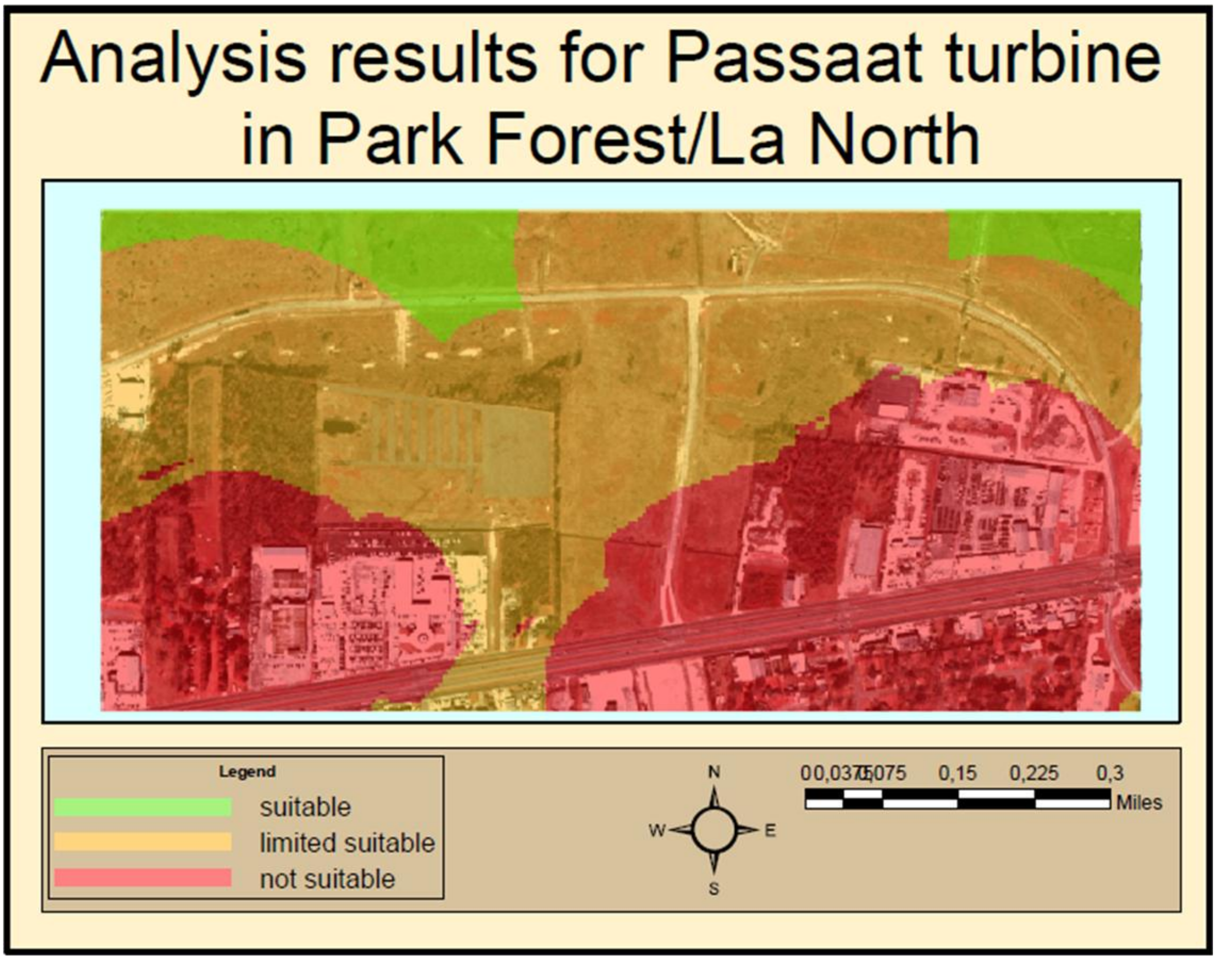


Figure 30: Final results of the analysis for the Passaat wind turbine

As shown in figure 30, the areas with no negative effect on the production of the small-scale wind power plant have been found. Due to the fact that there are neither slipstreams nor irregularities in the areas in the left and right upper corners, both are classified as most fitting installation sites. All other suitable results that were presented in figure 27 were put in the new class limited suitable. The areas classified as not suitable occur most likely because of the high amount of turbulences that are possible in this area. This is caused by the density of forests and buildings in the left and right lower corners. However the wind turbine will never be able to use its full capacity, due to the fact that the most common wind speed in the study area lies between 7 and 8 m/s. In 2011 the highest wind speed that has occurred over a persistent time is 13 m/s, so that the rated output of 1.4 kW at 16 m/s will never be reached.

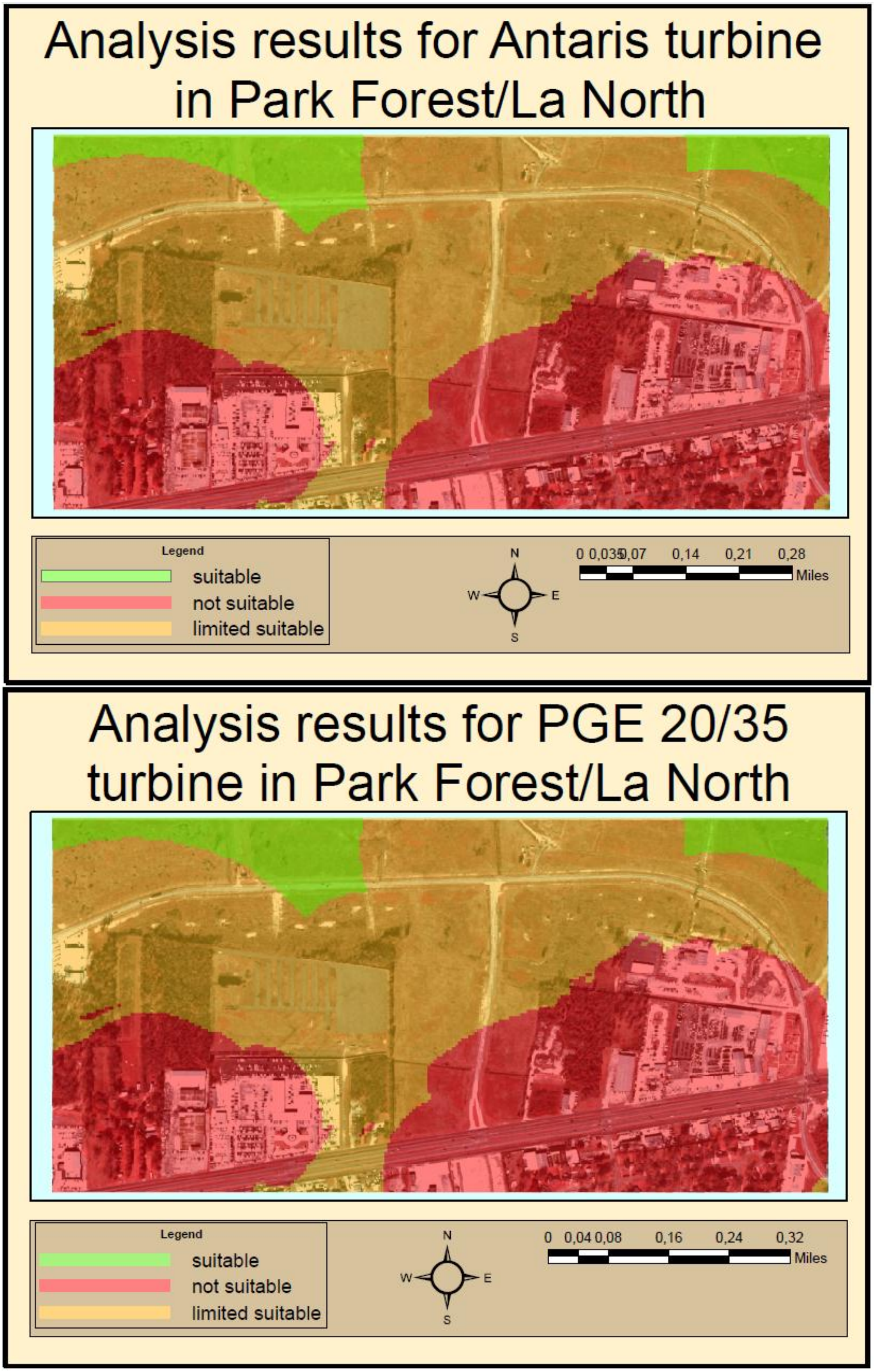


Figure 31: Final results of the analysis for the Antaris and PGE 20/35 wind turbines

As it can be seen in figure 31 the analysis results for the Antaris and PGE 20/35 small scale wind turbine are identical to the outcome of the Passaat wind turbine.

This appears due to sufficient start wind speeds of 1.8 m/s for the Antaris and 3.0 m/s for the PGE 20/35 in the limited suitable and suitable areas.

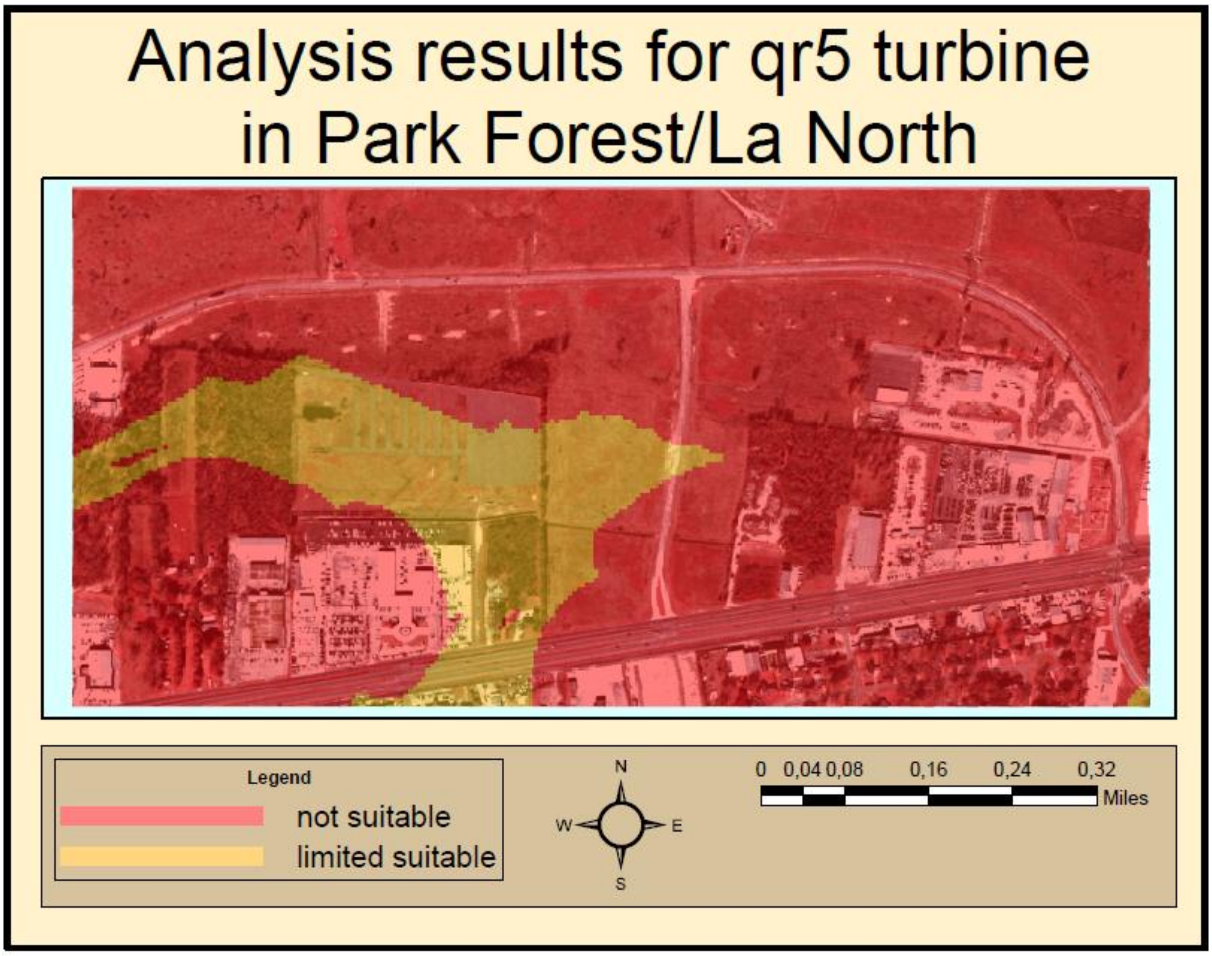


Figure 32: Final results of the analysis for the qr5 wind turbine

As it can be seen in figure 32 the qr5 is the worst suitable turbine in this study area. Due to the result that insufficient wind speeds are given in the upper right and upper left corners, the areas without slipstreams are classified as not suitable. The limited suitable areas have sufficient wind speed higher than the necessary starting speed of 4.5 m/s, but at least one and less than five affecting slipstreams.

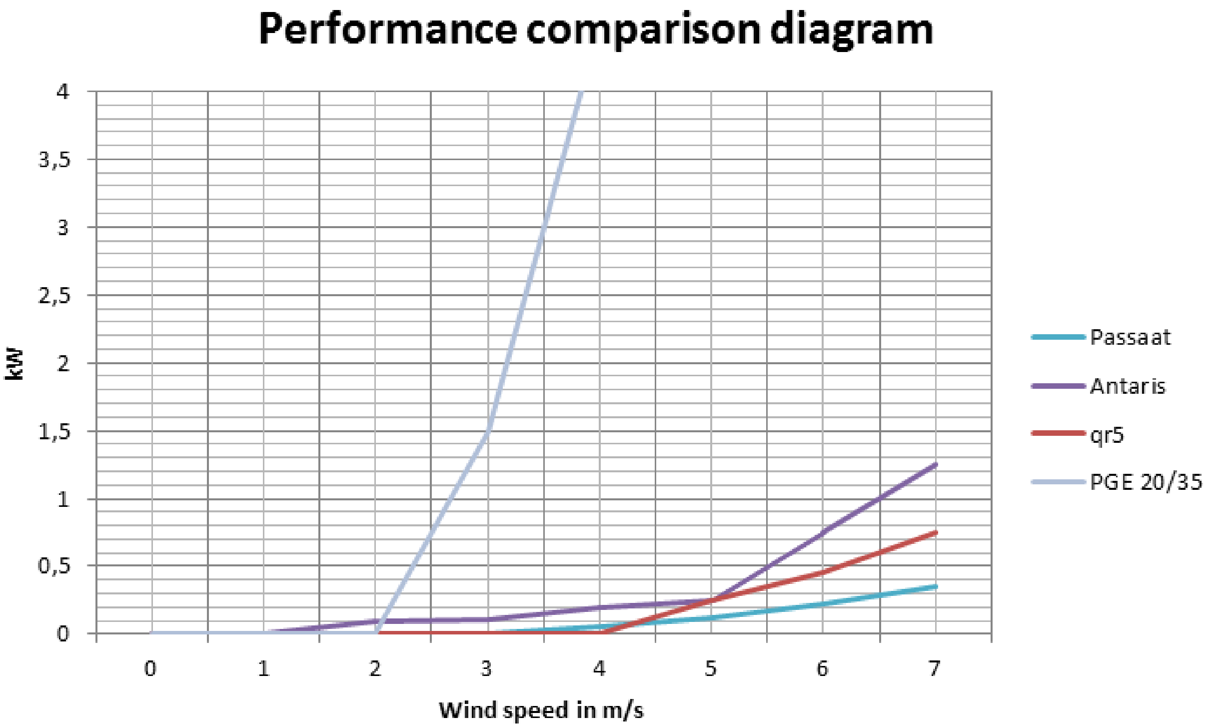


Figure 33: Detailed comparison of the four presented small-scale wind power plant's performances

Figure 33 shows a diagram that includes the performance curves of all in this thesis presented small-scale wind power plants. The fourth chapter presented the results of this research, whereas an identical result between the Passaat, Antaris and PGE 20/35 turbine could be determined. Therefore the performances curves can help to find the most productive turbine in the suitable areas. By looking on the wind speed distribution map in figure 27, the turbine’s most suitable marked sites involve a wind speed between 3 and 4 m/s. As it can be seen in figure 32 the PGE 20/35 wind turbine is with a production of 1.5 kW to more than 4 kW the most productive in this range if the costs are not considered. Because of the high production rate it would be a good solution for smaller companies or cooperative societies. By considering the high acquisition costs of the PGE 20/35, the Antaris wind turbine should be the first choice for a single operator in this area. However, in the case of that study area this turbine should only be used as a battery loader due to the low rated output of 100 W to 200 W.

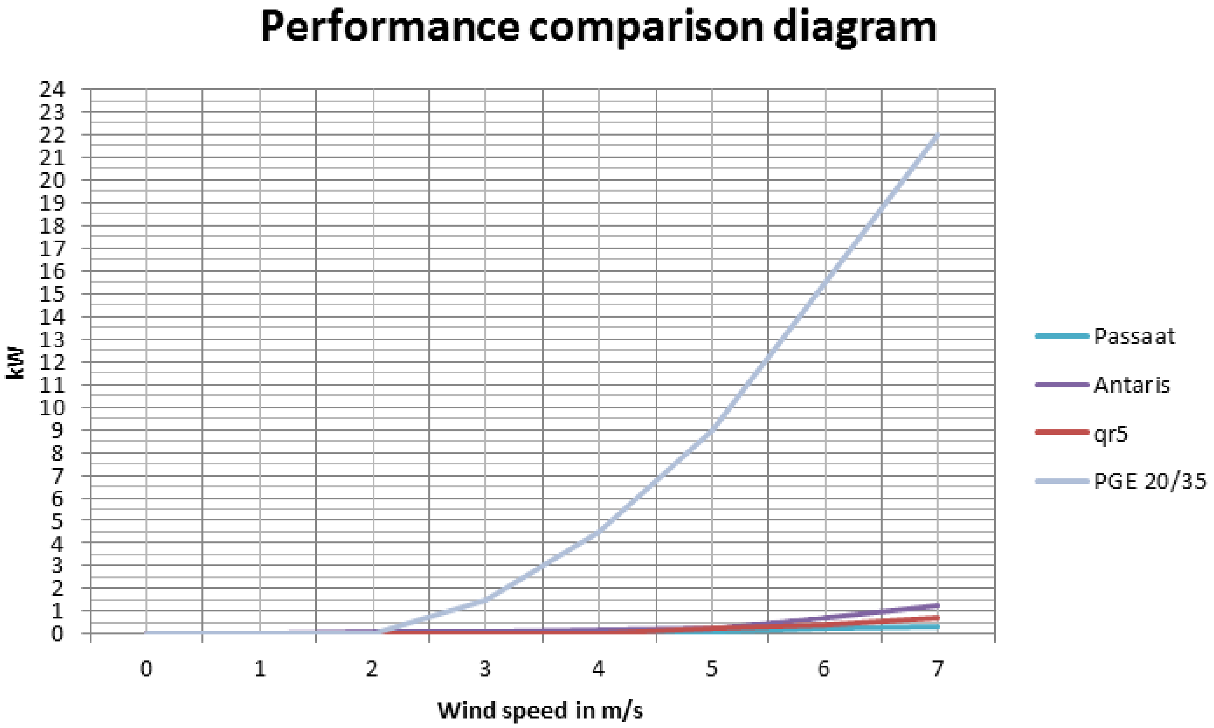


Figure 34: Overview comparison of the four presented wind turbine's performance curves

Figure 34 shows an overview of the in this thesis presented small-scale wind power plant's performance curves. As it can be seen here and in table 1 of chapter 2.3.1 the cheaper turbines Antaris, qr5 and Passaat reach their highest outputs at about 6.5 m/s, while the more expensive PGE 20/35 produces more current than the others at very low wind speeds. Therefore for the researched study area in Park Forest/La North a cheaper turbine would only be profitable as battery charger. The more expensive PGE 20/35 could not reach its full potential, but might produce a profitable amount of current even in regions with low wind speed.

The results for a study area in Villach, Austria should not differ much from the results in Park Forest/La North. The only difference lies in the slipstream of the mountain ranges that should also be considered. Therefore the calculation for buildings and forests that is shown in chapter 3.2 can be used as an approach, when considering the height of the mountains as parameter.
Furthermore it has to be considered that not all important factors have been implemented due to the fact that a computational fluid dynamic analysis would be necessary for a sufficient accuracy. Such factors include the consideration of a minimum distance between small-scale wind power plants and an additional analysis for occurring wake and tunnel effects that can cause a lot of turbulences for a wind turbine.

5. Discussion

This chapter deals with the discussion of the results. Therefore the hypothesis that was stated in chapter 1.3 and the expected results from chapter 1.5 are discussed and compared with the actual results of the research.

The hypothesis states that it is possible to estimate suitable installation sites for different types of small-scale wind power plants through the usage of a specific GIS and custom developed extensions. Furthermore the calculation of slipstreams around specific wind obstacles like buildings, forests and topography can be accomplished by using this GIS. This assumption has been investigated for the study area in Park Forest/La North, Louisiana, USA during this research. As shown in the results in chapter 4, the developed model cannot be fully implemented in ArcGIS. However, the model is able to show suitable locations for small-scale wind power plants in areas where slipstreams from specific wind directions are considered. The model also shows that customized open source extensions for shareware play an important role in the implementation processes nowadays. One positive aspect of the implementation in ArcGIS is the fact that the rehashed data layers can be filtered based on many requirements for a wide range of different types of small-scale wind power plants in the last step of the analysis.

Mostly all expected results that are listed in chapter 1.5 have been fulfilled. The first expectation was the development of a conceptual GIS-based analysis model for locating suitable installation sites for specific small-scale wind power plants. This has been accomplished after the design of an Entity Relationship diagram. This was necessary to be able to understand the relationships between the different parts of the thesis before designing the workflow. The second expectation was an evaluation of existing geodata regarding data quality and usability before using them in the analysis. This has been accomplished by describing the data in chapter 3.4. The last two expectations were the implementation of the conceptual analysis model in ArcMap for a study area in Baton Rouge, Louisiana, USA and the evaluation of its results by implementing it for a study area in Villach, Austria. This could only be partially fulfilled by implementing the model for the area in Park Forest/La North near Baton Rouge. The evaluation of the model in Villach, Austria could not be accomplished, but was conceptually discussed in the chapters 3 and 4.

6. Summary

In this part of the paper the working steps that had been accomplished in this thesis and their results are summarized. Furthermore a chapter that describes ideas and tasks for future projects is included.

6.1. Conclusion

It can be summarized that in the context of this research an Entity Relationship diagram and a conceptual model for locating suitable installation sites for different types of small-scale wind power plants has been developed. The model has been implemented in ArcGIS to accomplish an analysis in the study area of Park Forest/La North near Baton Rouge, Louisiana, USA. The evaluation of the model's results has yet to be accomplished. One idea is to evaluate the model using a study area in Villach, Austria. The results show the locations of slipstreams occurring from wind obstacles and where appropriate locations for different small-scale turbines are located. The wind data has been preprocessed with the help of the program WindRose PRO3 (Enviroware, 2012). It is able to transform comma separated value files into a wind rose, so that the main wind direction and wind speed can be determined. Due to the lack of LiDAR data the height of buildings and forests in the Park Forest/La North study area has been estimated by the usage of photogrammetric methods. The custom developed ArcGIS extension "XTools Pro" has additionally been used to perform the slipstream calculation (Data East, 2011). Other factors that influence the results can be filtered using the raster calculator tool. These factors include the soil type, terrain height, land cover, distance to power lines and the tolerance for slipstreams. As described in chapter 6.2, additional research factors should be implemented to increase the quality of the results of the analysis. These factors involve the consideration of a minimum distance between small-scale wind power plants and an additional analysis for wake and tunnel effects (Danish Wind Industry Association, 2012).

6.2. Further Perspectives

Additional influencing factors that have to be considered in future research are the wake and tunnel effects. The wake effect is associated with a wind turbine's casting of a wind shade in downwind direction. This is caused by generating electricity from the energy in the wind, so that the wind leaving the turbine must have lower energy content than the wind arriving in front. This fact follows directly from the principle that energy can neither be created nor consumed (Danish Wind Industry Association, 2012). Therefore a minimum distance between small-scale wind power plants has to be determined. The tunnel effect occurs between tall buildings or in a narrow mountain pass. Air is being compressed on the windy side of the buildings or mountains and its speed increases considerably between the obstacles. Therefore a higher wind speed can be reached between obstacles as long as the surface is as even as possible. If the obstacle's surface is too rough, a lot of turbulences occur, so that the wind is whirling in many different rapidly changing directions (Danish Wind Industry Association, 2012).

A way to make a much more accurate analysis for suitable installation sites of small-scale wind power plants would be the implementation of a computational fluid dynamic analysis. This has already been accomplished by the MIT project

“Full Breeze”, showing the feasibility of small-scale wind power plants on their campus from 2009 to 2010 (Full Breeze project team, 2010). To accomplish this, expensive software, accurate observation data from the last ten years and expensive measurement stations would be necessary. This was beyond the scope of this study. Furthermore, a publicly available Web-GIS application, which holds data from siting researches, should be implemented to promote an easier access to small-scale wind potential analysis for people who are interested in purchasing a turbine.

7. References

American Wind Energy Association, 2012. About AWEA. Available from: http://www.awea.org/learnabout/aboutawea/index.cfm [Accessed May 11, 2012]

Austrian Wind Energy Association, 2012. Windkraft aktuell – Interessensgemeinschaft Windkraft Windenergie Lobby Austrian Wind Energy Association. Available from: http://igwindkraft.at/index.php [Accessed May 11, 2012]

Austrian Wind Potential Analysis, 2011. AuWiPot – Windatlas und Windpotentialstudie Österreich (2009-2011). Available from: http://windatlas.at/index.html [Accessed May 11, 2012]

Bernhoff H., Eriksson S., Leijon M., 2008. Renewable and Sustainable Energy Reviews. Available from: http://www.sciencedirect.com/science/article/pii/S1364032107000111 [Accessed May 11, 2012]

Betz A., 1926. Wind-Energie und ihre Ausnutzung durch Windmühlen.

Black B., Flarend R., 2010. Historical Guides to controversial issues in America – Alternative energy, 131 – 135.

Braun Windturbinen GmbH, 2012. Kleinwindanlage Antaris 4,5 kW. Available from: http://www.braun-windturbinen.com/antaris-45-kw.html [Accessed May 11, 2012]

Bright Green Energy, 2009. Fortis Wind Turbines. Grid Connect and Battery Charging Wind Turbines. Available from: http://www.wirefreedirect.com/fortis_wind_turbines_and_genarators.asp [Accessed May 11, 2012]

Centre of Wind Energy Technology, 2005. Related links to initiatives. Available from: http://energy.nstl.gov.cn/MirrorResources/5131/relatedlinks.html [Accessed May 11, 2012]

Colorado – The official State Web Portal, 2012. Governor's Energy Office, Small Scale Wind Power. Available from: http://www.colorado.gov/cs/Satellite/GovEnergyOffice/CBON/1251599988408 [Accessed May 11, 2012]

Danish Wind Industry Association, 2012. The tunnel effect – Windpower Guided Tour. Available from: http://wiki.windpower.org/index.php/The_tunnel_effect [Accessed May 18, 2012]

Danish Wind Industry Association, 2012. Wake – Windpower Guided Tour. Available from: http://wiki.windpower.org/index.php/Wake [Accessed May 18, 2012]

Data East, 2011. DataEast – Xtools Pro. Available from: http://www.dataeast.com/en/XToolspro.asp [Accessed May 18, 2012]

Enviroware, 2012. WindRose PRO3. Available from: http://www.enviroware.com/portfolio/windrose-pro3/ [Accessed May 11, 2012]

European Wind Energy Association, 2012. About EWEA. Available from: http://www.ewea.org/index.php?id=5 [Accessed May 11, 2012]

Federal Emergency Management Agency, 2003. Guidelines and Specifications for Flood Hazard Mapping Partners. Available from: http://www.fema.gov/library/viewRecord.do?id=2206 [Accessed May 11, 2012]

Florida Center for (FCIT), 2012. ClipArt ETC – Cyclones and Anticyclones. Available from: http://etc.usf.edu/clipart/46600/46668/46668_cyclones.htm [Accessed June 6, 2012]

Fortis Wind Energy, 2008. Passaat Wind Turbine. Available from: http://www.fortiswindenergy.com/products/wind-turbines/passaat [Accessed May 11, 2012]

Full Breeze project team, 2010. Feasibility Study – Project Full Breeze. Available from: http://web.mit.edu/wepa/Full%20Breeze%20Report.pdf [Accessed May 11, 2012]

Halbhuber W., 2009. Diplomarbeit – Betrieb von Kleinwindkraftanlagen – Ein Überblick über Markt, Technik und Wirtschaftlichkeit.

Internationaler Marktplatz Windenergie, 2012. Kleinwindanlage ANTARIS 3.5 kW. Available from: http://www.wind-turbine.com/marktplatz/marktplatz_anzeige,195,Kleinwindanlage-ANTARIS-3-5-kW.htm [Accessed May 11, 2012]

International Network for Sustainable Energy (INFORSE), 2010. Dieret: Wind Energy. Available from: http://www.inforse.org/europe/dieret/Wind/wind.html [Accessed May 18, 2012]

JBS Solar and Wind, 2012. Energy Sensible Living for a Brighter Future, PGE 20/35 Wind turbine. Available from: http://www.2jbs.com/windturbines/pgeenergie3550kw.html [Accessed May 11, 2012]

Kyoto in the home, 2011. Micro-Wind – Installation. Available from: http://www.kyotoinhome.info/UK/wind/installation.htm [Accessed May 18, 2012]

Levy M., 2007. Why the Wind Blows – A History of Weather and Global Warming, Monsoon and other big winds, 107-112.

Louisiana Department of Environmental Quality (LDEQ), 2012. Available from: http://www.deq.louisiana.gov/portal/ [Accessed May 14, 2012]

Louisiana Oil Spill Coordinator's Office (LOSCO), 2012. About LOSCO. Available from: http://www.losco.state.la.us/about.htm [Accessed May 14, 2012]

Louisiana State University (LSU), 2012. Atlas: The Louisiana Statewide GIS. Available from: http://atlas.lsu.edu/ [Accessed May 14, 2012]

Louisiana State University (LSU), 2012. Louisiana Office of State Climatology. Available from: http://www.losc.lsu.edu/hourly_site_map.html [Accessed May 14, 2012]

Minney R., Rogers P., 2008. An introduction to quietrevolution and the qr5 wind turbine. Available from: http://www.all-energy.com.au/userfiles/file/Philippa_Rogers_presentation.pdf [Accessed May 11, 2012]

Petersen E., Troen I., 1989. European Wind Atlas. Available from: http://www.windatlas.dk/Europe/About.html [Accessed May 11, 2012]

Sparkling Science, 2011. Sensors4All. Available from: http://geoweb05.cti.ac.at/sensors4all/index.php?title=Main_Page [Accessed May 21, 2012]

Statistik Austria, 2010. Population Censuses. Available from: http://www.statistik.at/web_en/statistics/population/population_censuses/index.html [Accessed May 13, 2012]

Strahler A., Strahler A., 2006. Introducing physical geography. Winds and Global Circulation, 156 – 162.

The Spark, 2012. Carymoore Center Wind Turbine. Available from: http://www.thespark.co.uk/uploads/images/green%20pics/CarymoorCentre-copy.gif [Accessed May 11, 2012]

Tradekey, 2012. Energie PGE, Canada. Available from: http://www.tradekey.com/company/Energie-PGE-1358331.html [Accessed May 11, 2012]

University of Applied Sciences Frankfurt am Main, 2012. Wind Area. Available from: http://www.fh-frankfurt.de/de/fachbereiche/fb1/ansprechpartnerinnen/professorinnen/klaerle/forschung/wind_area.html [Accessed June 13, 2012]

U.S. Census Bureau, 2011. 2010 Census. Available from: http://2010.census.gov/2010census/ [Accessed May 13, 2012]

U.S. Census Bureau, 2011. TIGER/Line® Shapefiles. Available from: http://www.census.gov/geo/www/tiger/tgrshp2011/tgrshp2011.html [Accessed May 14, 2012]

U.S. Department of Energy, 2012. Wind Powering America. Available from: http://www.windpoweringamerica.gov [Accessed May 11, 2012]

U.S. Energy Information Administration (EIA), 2012. Annual Energy Review 2010. Available from: http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf [Accessed May 11, 2012]

U.S. Geological Survey (USGS), 2006. National Elevation Data. Available from: http://ned.usgs.gov/ [Accessed May 14, 2012]

U.S. Geological Survey (USGS), 2010. Earth Resources Observation and Science Center. Available from: http://eros.usgs.gov/ [Accessed May 14, 2012]

U.S. Geological Survey (USGS), 2012. Ecosystems Mission Area. Available from: http://www.usgs.gov/ecosystems/ [Accessed May 14, 2012]

U.S. Geological Survey (USGS), 2012. Maps, Imagery and Publications. Available from: http://www.usgs.gov/pubprod/ [Accessed May 14, 2012]

The Worlds of David Darling, 2012. The Encyclopedia of Alternative Energy and Sustainable Living – small wind turbine siting. Available from: http://www.daviddarling.info/encyclopedia/S/AE_small_wind_electric_system_siting.html [Accessed May 18, 2012]

World Wind Energy Association (WWEA), 2012. Small Wind World Report Summary 2012. Available from: http://www.wwindea.org/webimages/WWEA%20Small%20Wind%20World%20Report%20Summary%202012.pdf [Accessed May 11, 2012]

World Wind Energy Association (WWEA), 2012. WWEA Quarterly Bulletin – Wind Energy Around the World. Available from: http://www.wwindea.org/webimages/WWEA_Quarterly_Bulletin.pdf [Accessed May 11, 2012]

XWeather, 2005. Foehn Wind. Available from: http://www.xweather.org/foehn-wind [Accessed June 6, 2012]

8. List of Figures

9. List of Tables