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Introduction

This book is about the meteorological aspects of wind energy.[1] There are mainly two areas which are ‘affected by the wind’: wind resource estimation and loads. This book will focus on the meteorological aspects of wind resources, but loads will also be discussed, mainly in the chapter on turbulence (Chapter 6).

The structure of the book is, as a general principle, that each chapter will describe one subject and start with the basics, then the intermediate and lastly the more advanced topics of each subject. Depending on what you are interested in, in the various subject areas, you can stop when you have reached the level you are looking for. At the end of each chapter I have put some exercises: some are quite basic, just using what you have learnt, some more technical requiring calculations, etc. and some are more open-ended, just to get you to think about things. In other cases, where it fitted better with the flow of the chapter, I have put exercises right in the text; they are intended for you to pause and think. Some of the exercises are solved in the text following the exercise, because the point is so important, that you need to know the answer in order to proceed, others are solved in the Answers appendix. The answer to each of the exercises can be found in the back (Appendix B). To solve the exercises all you need is pen, paper and a pocket calculator, but you will make your life much easier if you use a spreadsheet.

In many places in the text you will find *references* to books, articles, websites, etc. These are meant, firstly to follow the academic tradition of acknowledging other peoples’ work, but also to point you in a specific direction, where you will be able to learn more. In this day and age, many things can be found for free on the internet. This is, unfortunately, not always the case with references, so consulting a given reference might not always be as easy as just a click away.

As a general principle, I have tried to make the book a journey, and one where I walk along with you. This might have led to a bit of a chatty style in places, but I think overall, by presenting the subjects in this way, your learning should be helped significantly.

[1] But I am sure most of the chapters can also be used as a good general introduction to the field of general meteorology and in particular, the field called boundary-layer meteorology.

Meteorology for Wind Energy: An Introduction, First Edition. Lars Landberg.

The sequence of the chapters is as follows: First we start with a chapter on *meteorological basics* (Chapter 2) where the scene will be set and some fundamentals of general meteorology will be covered. We will then discuss *measurements* (Chapter 3), where some measurement philosophy, theory and basics will be covered. Whether measurements are carried out by means of a mast or a remote-sensing device, the result could be a picture of the vertical structure of the atmosphere at the measuring location, the following chapter (Chapter 4) therefore covers the theory of this vertical structure, often called the *wind profile*. The wind profile is the result of atmospheric *flow* on many scales, and in many ways this is like being shown the needle and then asked to describe the haystack! But understanding the various flows makes us able to infer the profiles (and in many cases vice versa), so these flows will be described in the next chapter (Chapter 5). Two further aspects will then be covered: *turbulence* (Chapter 6), which is quite a technical subject, but I will do my best to explain and then, finally, *wakes* (Chapter 7), that is the downstream reduction of the wind speed due to the wind turbine.

Having gone from measurements via flow on all scales to wakes, the circle is complete in some sense; however, in order to understand all of this in more detail, various models have been introduced and it is therefore appropriate to have a chapter on the general aspects of *modelling* (Chapter 8), where no new models will be introduced, but the more philosophical and theoretical aspects of modelling will be discussed.

Finally, some conclusions will be drawn (Chapter 9) and the list of references will be given. As a quick way of summarising the most important formulae and points, you will, in Appendix A, find a ‘cheat sheet’, which can be used as a quick reference guide. In Appendix B answers to all the exercises will be given.

The book also has an accompanying website (larslandberg.dk/windbook, see QR code in margin), where data for some of the exercises can be found. Here you will also find a few videos, an area where I will discuss each chapter further (in cases where new information becomes available), list the errata (if any!) and finally I will post news items of various kinds there as well.

Once you have read this book, it is my goal and hope that you will have a basic understanding of all the relevant areas of meteorology needed for working in wind energy. As mentioned I will have cut some corners, so I also hope that you will be in a position to continue your learning in the areas that particularly interest you.

You will also realise, as you read through the chapters, that most questions we can ask to try to understand any of the topics discussed in this book can rarely be answered with a straight ‘yes’ or ‘no’; instead the answer is often: ‘It depends’, and one of my main goals of the book is also to enable you to qualify that very simple statement, to ask the right questions and to be able to state what this or that actually depends on.

You might as well get used to the fact that I will ask you to work with me solving different exercises as we go along, so here is the first one, where we, step by step, will derive one of the fundamental relations in wind energy:

Exercise 1.1 *Imagine for a short while that you have the front frame of a football goal dangling in mid air (might be a bit difficult to, but the idea is that we want to look at a box of air), and furthermore, that it is exactly 1×1 m. Imagine also that the wind is blowing through the frame at a speed of 10 m/s. How many cubic metres of air will pass through the goal in 1 s?*

As mentioned above, the expression we will get out at the end of these derivations is quite fundamental, so I will solve the exercise here; however, please give it a try yourself first. As you will see, I have broken this first exercise down into a lot of small steps, to ensure that you can follow me, and get used to this way of working.

The area is 1×1 m, and at a wind speed of 10 m/s, a box 10 m long will pass through in 1 s, viz

$$10 \times 1 \times 1 = 10 \text{ m}^3 \tag{1.1}$$

of air will pass through.

Exercise 1.2 *Assume the density is ρ kg/m^3, how many kg of air does then blow through the goal?*

We have 10 m^3 of air, so we get the mass of the air going through the goal, m, to be:

$$m = 10 \cdot \rho \tag{1.2}$$

Note that we are not using the actual value of ρ (which is around 1.225 kg/m^3), since we are trying to get to a general expression.

Exercise 1.3 *Assume now that the wind speed is u m/s (instead of the 10 m/s), what would the mass, m, of the air going through the 1 m^2 goal frame be?*

Generalising what we have just found, we get:

$$m = u\rho \tag{1.3}$$

We now have the first part of an expression that we are working on deriving, the second part has to do with the kinetic energy, so

Exercise 1.4 *What is the definition of kinetic energy?*

This can be found in many books on fundamental physics and it is:

$$E_{kin} = \frac{1}{2} m u^2 \tag{1.4}$$

We are now able to answer the question that I have been looking for an answer to:

Exercise 1.5 *Combine what we have found out about the mass of the air going through the goal frame with the equation for kinetic energy, to see how much kinetic energy goes through 1 m^2 of air.*

Combining the two relations, we get

$$E_{kin} = \frac{1}{2}mu^2 = \frac{1}{2}(\rho u)u^2 = \frac{1}{2}\rho u^3 \tag{1.5}$$

Which is the amount of kinetic energy that blows through 1 m^2.

This is one of the more fundamental equations in wind energy, showing that the energy is propositional to the *cube* of the wind speed. A different way of explaining what this equation says, is that looking at 1 m^2 of the rotor plane of a wind turbine, this is the maximal energy available for the wind turbine to convert into electricity.[2]

You are about to go on a tour through quite a few different topics, both with regard to breath of coverage, but also mathematically, some topics are easy to approach, but others, like turbulence, are much more difficult. But, if you just allow yourself to at least read through those parts, too, you will gain a bit more understanding, and when the topic pops up at a later stage, you will find the terms familiar and your understanding will gradually increase.

[2] There is a law, called Betz's law, that says that no wind turbine can capture more than 16/27 (≈59.3%) of the kinetic energy in the wind.