Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Master Thesis

Marcel Schütt

Upscaling, concept design and comparison of concepts of future three-bladed 20 MW offshore wind turbines

Fakultät Technik und Informatik
Department Maschinenbau und Produktion

Faculty of Engineering and Computer Science
Department of Mechanical Engineering and Production Management

Marcel Schütt

Upscaling, concept design and comparison of concepts of future three-bladed 20 MW offshore wind turbines

Master Thesis submitted in the course of the Master's degree examination

in degree course Calculation and Simulation in Mechanical Engineering
in Department of Mechanical Engineering and Production Management
of Faculty of Engineering and Computer Science
at the Hamburg University of Applied Science

main-examiner: Prof. Dr.-Ing. Vera Schorbach, HAW Hamburg
sub-examiner: John M. Obrecht, Ph.D., Siemens Gamesa Renewable Energy

date of submission: 4th September 2017

Summary

Marcel Schütt

Title of the paper

Upscaling, concept design and comparison of concepts of future three-bladed 20 MW offshore wind turbines

Keywords

Upscaling, concept design, comparison, UpWind, DTU, 20 MW wind turbine, 10 MW wind turbine, state of the art wind turbines, modern wind turbines, technical specifications, history of wind turbines, drive train concepts, teetering hub, VDI 2225, square-cube law

Abstract

Inside this report initially the scientific background on the history of wind turbines, on modern wind turbines and on upscaling are explained. Subsequently, several so-called “State of the Art” turbines (≥ 10 MW, resp. ≥ 8 MW) are described and their technical specifications are listed. A turbine is selected and the parameters are scaled up to 20 MW nominal power output, according to the theoretical basics. Furthermore, aspects from current scientific literature are considered (concept design). Finally, an objective comparison of two 20 MW wind turbines is carried out, and a recommendation for further research projects at HAW Hamburg is made. The work finishes with a summary of the results as well as an outlook.

Marcel Schütt

Thema der Masterarbeit

Hochskalierung, Konzeptgestaltung und Vergleich von Konzepten von zukünftigen dreiblättrigen 20 MW offshore Windenergieanlagen

Stichworte

Hochskalierung, Konzeptgestaltung, Vergleich, UpWind, DTU, 20 MW Windenergieanlage, 10 MW Windenergieanlage, Stand der Technik Windenergieanlagen, moderne Windenergieanlagen, technische Spezifikationen, Geschichte der Windenergieanlagen, Triebstrangkonzepte, Pendelnaben, VDI 2225, Square-Cube-Gesetz

Kurzzusammenfassung

Diese Arbeit umfasst zunächst eine Darstellung der wissenschaftlichen Grundlagen zu den Themen Geschichte der Windenergieanlagen, moderne Windenergieanlagen sowie Hochskalierung. Im Anschluss daran werden mehrere sogenannte „State of the Art“ (Stand der Technik) Turbinen (≥ 10 MW, bzw. ≥ 8 MW) beschrieben und deren technischen Spezifikationen aufgelistet. Es wird eine Turbine ausgewählt und die Parameter werden entsprechend den theoretischen Grundlagen auf 20 MW Leistung hochskaliert. Weiterhin werden Aspekte aus aktueller wissenschaftlicher Literatur berücksichtigt (Konzeptgestaltung). Schlussendlich wird ein objektiver Vergleich zweier 20 MW Windenergieanlagen durchgeführt, aus dem eine Empfehlung für zukünftige Forschungsvorhaben an der HAW Hamburg hervorgeht. Die Arbeit schließt mit einer Zusammenfassung der Ergebnisse sowie einem Ausblick.

Acknowledgements

The present work was written as part of the Master's degree examination in the course "Calculation and Simulation in Mechanical Engineering" at the Hamburg University of Applied Science.

Special thanks to

- *Prof. Dr.-Ing. Vera Schorbach* for the provision of the interesting topic as well as for the support and the suggestions in the preparation of the work,
- *John M. Obrecht, Ph.D.* for the support and the suggestions in the preparation of work,
- *all employees and colleagues* of HAW Hamburg, who supported me with problems and questions.

Contents

List of figures

List of tables

Nomenclature

Latin characters

A	Swept area of rotor [m²]
A	Area (even projected area) [m²]
C	Width of blade [m]
$C_{l\alpha}$	Slope of lift-curve [-]
c	Blade chord [m]
c_A	Lift coefficient [-]
c_W	Drag coefficient [-]
D	Diameter [m]
D	Dimension [-]
E	Glide ratio [-]
F	Force [N]
H	Height [m]
I	Inertia [kgm²]
i	Ratio (gearbox) [-]
L	Length [m]
L_{CoG}	Distance to the center of gravity [m]
M	Moment [Nm]
N	Number of blades [-]
P	Power [kW]
Q	Torque [Nm]
q	Standardized factor [-]
R	Radius [m]
t	Thickness of blade [m]
u	Wind speed [m/s]
v	Wind speed [m/s]
W	Weight [t]
W_t	Technical Value (VDI 2225) [-]
y	Distance to the neutral axis [m]

Greek characters

α	Tilt angle (rotor) [deg]
β	Blade cone angle [deg]
γ	Lock Number (mass number) [-]
λ	Tip speed ratio [-]
ρ	Air density [kg/m^3]
σ	Stress [N/m^2]
Ω	Rotational speed [rpm]
ω	Tip speed [rpm]

Abbreviations

AEP	Annual Energy Production
CAD	Computer Aided Design
CAPEX	Capital Expenditures
CFD	Computational Fluid Dynamics
DTU	Technical University of Denmark
ECN	Energy research Centre of the Netherlands
EU	European Union
GL	Germanischer Lloyd
IEC	International Electrotechnical Commission
IEC class	Wind regime class based on IEC
IPC	Individual Pitch Control
LCoE	Levelized Cost of Energy
NREL	National Renewable Energy Laboratory
PMG	Permanent Magnet (synchronous) Generator
R&D	Research and Development
VDI	Association of German Engineers (Verein Deutscher Ingenieure)
WMC	Knowledge Centre Wind turbine Materials and Constructions

Chapter 1

Introduction

1.1 Research studies on large wind turbines at HAW Hamburg

To protect the climate for the future and to promote the energy turnaround, innovative solutions and new concepts for renewable energy and energy efficiency need to be developed [1]. For this reason, the Hamburg University of Applied Science (HAW Hamburg) has planned to do profound research studies on large wind turbines, in which many different questions regarding these future relevant topics are to be investigated.

The aim is to investigate the potentials of reducing the Levelized Cost of Energy (LCoE) of future offshore wind turbines, with a maximum rated power output of 20 MW. In this context, the focus is on three-bladed wind turbines as well as on two-bladed wind turbines. In a first step, turbines are to be designed conceptually. After that load simulations and structural interpretations are to be done. It is planned to compare three-bladed turbines with equivalent two-bladed turbines, because a holistic and objective comparison between three-bladed and two-bladed wind turbines is still a gap in previous research studies. In order to be able to implement a comparison between three-bladed and two-bladed wind turbines, a suitable 20 MW reference turbine (three-bladed turbine) has to be selected.

In this thesis, this problem is to be looked at closer, whereby the exact task is described in the following chapter. In principle, this thesis is part of the preliminary work for the planned research studies. After the selection, the chosen reference turbine can be reconfigured into a two-bladed turbine (part of upcoming projects, not in this thesis), so that an equivalent comparison between three-bladed and two-bladed wind turbines can be made.

1.2 Task and aim of this work

As described in the previous chapter, a 20 MW three-bladed offshore reference wind turbine needs to be defined for research purpose at Hamburg University of Applied Science (HAW Hamburg). This Master thesis is the preliminary work for choosing the reference turbine. Therefore, on the basis of a literature research, wind turbines are to be listed, which are in accordance to the current "State of the Art" (≥ 8 MW) or which have already been defined for a research purposes (≥ 10 MW). As one approach the 20 MW wind turbine from the research report "UpWind – Design limits and solutions for very large wind turbines" published in 2011 should be considered.

The aim of this thesis is to do a comparison of at least two future (20 MW) three-bladed offshore wind turbines. Therefore, it is necessary to scale up at least one of the other wind turbines, which are selected from the compilation before. This part includes the definition of useful upscaling laws and upscaling relations. After the upscaling work, some aspects to finish the concept design, for example aspects from current scientific literature, can be considered. These aspects have to be defined according to the upscaling results. For the comparison suitable criteria have to be defined as well. The final aim of the comparison is to give a recommendation for upcoming research projects, with a focus on the question of possible 20 MW reference turbines. As described before, a suitable reference turbine will be required within the first step of planned research studies to reconfigure it into a two-bladed turbine.

1.3 Approach

In order to get a general overview of wind energy and wind energy turbines, the first part of this work (Chapter 2) deals with the depiction of the history and the scientific background, focusing on turbines for the purpose of energy production. A further focus of this chapter is on the background of the so-called “Upwind Research Project”, in which a 20 MW research turbine was designed. The most important aspects of this research project are summarized. Another part of the scientific background are the upscaling laws and upscaling relations as well as the knowledge from current scientific literature. These aspects are also explained in this chapter.

In the following Chapter 3, turbines are described, which correspond to the current state of the art. Three kinds of turbines are listed: turbines designed for research purposes (for example the 20 MW UpWind turbine), as well as turbines that are currently available on the market. The third category includes turbines, which are not classifiable. The listed turbines are the largest of their kind. In addition to a basic description of the turbine, the focus of this chapter is on the corresponding dimensions and technical data. These are shown in tabular form for the sake of clarity. The dimensions and technical data of the “UpWind 20 MW Turbine” are also regarded in this chapter.

Subsequently, Chapter 4 focuses on the selection of at least one turbine for upscaling. The turbines from Chapter 3 are evaluated according to the method of VDI 2225[1], which is first explained in this context and then applied to the listed turbines. For that, suitable evaluation criteria have to be defined.

The upscaling of the selected turbine (if applicable turbines) takes place in Chapter 5. In this case the basic upscaling laws and relations are to be applied to the selected turbine (if applicable turbines) as well as the knowledge from current

---

[1] The “VDI 2225” is a standard by the Association of German Engineers for design engineering methodics, engineering design at optimum cost and dimensioning [42].

scientific literature. The results are again tabulated. Finally, the results are critically analyzed within a discussion.

An objective comparison of the UpWind 20 MW Turbine with the upscaled turbine (if applicable turbines) is in the foreground of the following Chapter 6. In principle, the comparison is divided into three steps. At first the pros and cons of both 20 MW turbines are listed and compared. Second, the technical parameters are tabulated and compared itself. And third, on the basis of both, suitable comparison / evaluation criteria are to be defined and a structured and a methodic comparison / evaluation is to be carried out according to the method of VDI 2225, like in Chapter 4. The resulting “best” turbine is to be highlighted and recommended.

Chapter 7 summarizes the results of the work. The thesis is completed with an outlook for future research questions and projects.

Chapter 2

History and scientific background

As the first step into this thesis, the next chapter will summarize the historical development of wind turbines starting at the end of the 19th century. That is because no relevant occurrences are happened in relation to the energy production purpose of wind turbines before this date. Other purposes for example to grind grain or to pump water are not important for the focus of this thesis. After an overview of the history Chapter 2.2 presents the functionality and the design of modern wind turbines. This includes a tabled compilation of the subsystems, respectively the main components. Subsequently to the historical development and the design of modern wind turbines, Chapter 2.3 will give a short introduction and overview on the “UpWind Research Project”. The UpWind Project represents the vision of the future that will be adopted for this thesis. The scientific background is completed by Chapter 2.4, which deals with the principles of upscaling and the knowledge from current scientific literature.

2.1 History of wind turbines

The history of wind energy began in 1891, with the initial operation of the first wind turbine by Poul La Cours in Askov, Denmark. This turbine was built based on the standard of traditional windmills and had four blades. Via a shaft a dynamo was driven, that produced electric power (direct current) [2]. In the following years a few additional turbines were installed and experiments were done, always with the aim of improving the existing installations. Also many theories and scientific principles had been developed at this time. In 1920 for example, Albert Betz formulated the “Betzian theory”, which says that the maximum profit of the wind is limited to 59.3 % of the overall power that is contained in the wind [3].

In 1931 a turbine was built in Balaklava on the Crimea, Ukrain, which was essential for further research. The turbine with the name WIME D-30 reached a nominal output of approximately 100 kW with a three-bladed rotor with a diameter of 30 m [2, 4]. It was followed by many other turbines with larger rotor diameters and higher power ratings. In 1941 the so-called “Smith-Putnam turbine” started its operation in Vermont, United States. With a rotor diameter of 53.3 m, a nominal power output of 1,250 kW, a two-bladed rotor made of stainless steel, a hydraulic blade adjustment and a synchronous generator, the turbine was crucial for the state of the art at that time [2, 4, 5, 6]. Interestingly, this turbine already had many of the characteristics of today’s installations. For reasons of economic viability and due to numerous deficiencies in operation, these and similar turbines did not become established. The turbines were simply too expensive because of the currently low prices of primary energy (coal, oil, etc.). In addition to this, there were a number of technical faults and defects as well as the failure of components, for example the failure of the blades (“Smith-Putnam turbine” in 1945 [5]), by which the costs increased further.

In the following years the interest in wind energy decreased, not at least because of the Second World War and its economic consequences. After the war, once again smaller turbines were in the focus. In 1957, for example, the Danish “Gedser-Turbine” with a three-bladed rotor, a rotor diameter of 24 m and a rated output of 200 kW started its operation [2, 5]. In the following year (1958) the so-called W34 or “Hütter-Turbine” was built in Germany. This two-bladed turbine had a rotor diameter of 34 m, but only a nominal output of 100 kW [2]. Nevertheless, this system characterizes today’s installations in numerous features. Especially the lightweight construction used by Ulrich Hütter was trend-setting, for example the use of blades of glass fiber composites.

It was only after the oil crisis in 1973 that the interest in the use of wind power increased again and became public effective. In the United States, for example, the NASA was given the task of developing solutions for an independent energy supply without oil. Also in Europe the awarding of several research projects began to promote the development of modern wind energy turbines [2, 4, 5]. In the following Table 01 an extract of these projects, which were partly government-funded, is shown. Further projects and research turbines exist.

Year	State	Name	Type	Rated power	Rotor diameter
1978	Denmark	Tvind	3-bladed	2000 kW	52 m
1979	United States	MOD-1	2-bladed	2000 kW	61 m
1980	United States	MOD-2	2-bladed	2500 kW	91 m
1982	Sweden	WTS-3	2-bladed	3000 kW	78 m
1982	Germany	Growian	2-bladed	3000 kW	100 m
1987	United States	MOD-5B	2-bladed	3200 kW	98 m
1990	Germany	WKA-60	3-bladed	1200 kW	60 m
1993	Sweden	Aeolus II	2-bladed	3000 kW	80 m

Table 01: Wind turbine projects (in excerpts 1970s, 1980s, 1990s), (based on [2, 4, 5, 7])

From today's point of view, many of these installations failed, not at least because of the time pressure (short development periods were given) by the employer and authorities. The turbines were often too big, were built too early and were too expensive. Possible problems which might arise during operation of such large turbines, e.g. due to different wind conditions, were inadequately considered, so that the operating characteristics of the turbines were simply not good and the defects became more frequently [4].

In addition to the test installations, the commercial and private use of wind power plants was also focused after 1973 [2]. With the knowledge gathered since 1891 and the research projects of the 1970s, 1980s and 1990s, the basis for today's reliable and profitable turbines was set. The systems are continuously grown in their size (rotor diameter) and their rated output. An overview is shown in Figure 01.

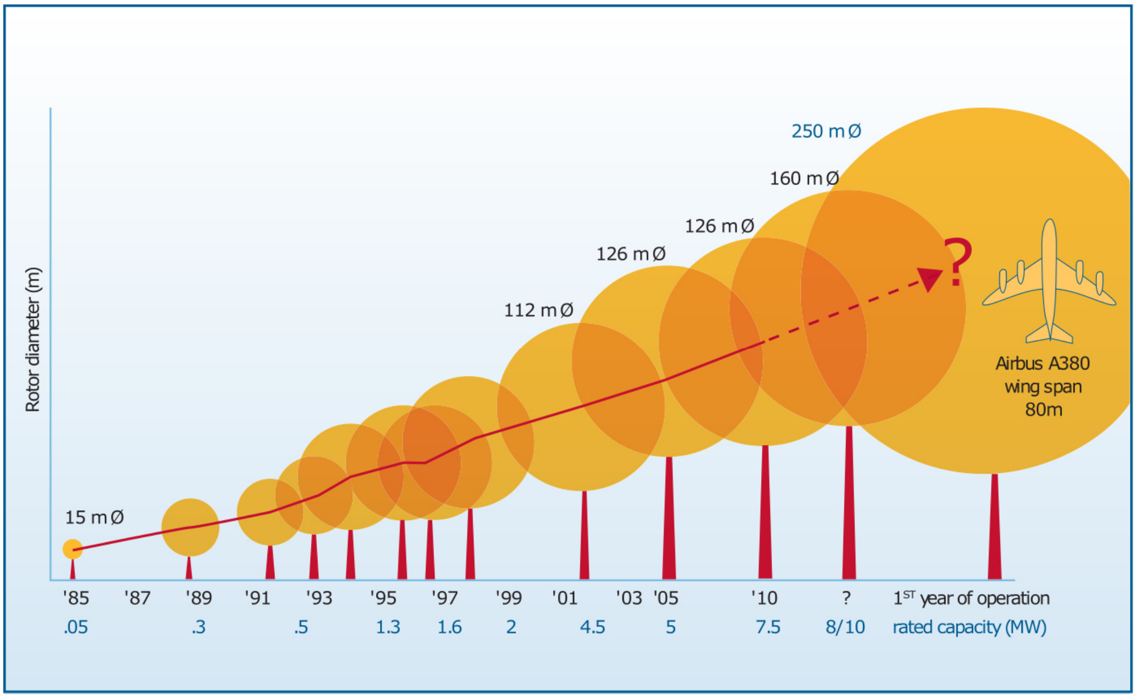

Figure 01: Evolution of turbine size, (Source: [8])

In general, it can be said that all these “modern installations” differ only slightly conceptually. Regarding the functionality and the underlying energy conversion process, there are almost no differences. Particularly in view of the installations of the 21st century, only little significant innovations can be found. However, especially noticeable is that three-bladed turbines are established more than two-bladed turbines today. This had probably many reasons in the past. As an example, three-bladed turbines were objectively better in structurally dynamics and in operation loads than two-bladed turbines. Subjectively it is possible that the failure of the two-bladed research turbines of the 1970s and 1980s also played a role. Finally, the design of “modern turbines” is explained below.

2.2 Modern wind turbines

Modern wind turbines use the lift force generated by an airflow on an aerodynamically shaped rotor blade to drive the rotor [4]. The resulting mechanical energy, in form of a torque, is subsequently converted into electricity by a generator. This process takes place immediately and still in the nacelle of the turbine. The connection to the electricity grid is via a cable that runs in the tower. In general, it is important to note that the power output is not constant due to fluctuations in the incoming airflow. However, an almost constant output can be achieved by using an intelligent control of the turbine system, which limits the production below the fluctuations [5].

As indicated in the previous chapter, modern installations only differ little in their functionality, respectively their energy conversion process. Regarding their subsystems and main components there are some options, which are shown in Table 02.

Sub system / Main component	Option
Rotor orientation	*Mainly:* upwind, *alternative:* downwind
Rotor control	*State of the Art:* pitch, *out of date:* stall
Number of blades	*Mainly:* three, *alternative:* two
Blade material	Glass fiber reinforced plastic (GRP), carbon fiber reinforced plastic (CRP), other composite material
Hub design	Rigid, teetering, hinged
Yaw system	*Mainly:* active yaw, *alternative:* free yaw
Rotor speed	*State of the Art:* variable speed, *out of date:* fixed speed
Generator	Synchronous generator, induction generator
Gearbox	Gearbox, direct drive
Tower (material)	Concrete, steel, framework (steel)

Table 02: Characteristics of modern wind turbines, (based on [5])

At this point, a detailed description of all components of a wind energy installation will be omitted. If necessary, for example [4] and [5] provide profound explanations.

Further differences of modern turbines are found in the design methods and in the aerodynamic profiles of the blades. These are different from manufacturer to manufacturer. Due to the versatility of the construction methods as well as the high complexity of the aerodynamic blade profiles, it is difficult to give a short overview. In respect to this, further literature, e.g. [4] and [5], can be recommended again. Furthermore, a short overview of the blade design basics is shown in Chapter 5.2.2, in course of the concept design of the upscaled turbine.

At this point the description of modern turbines is done. The following chapter will be take a look at the future. The UpWind project shows one possibility of it.

2.3 UpWind 20 MW (project overview)

In March 2006, the largest European R&D project in the field of wind energy called “UpWind” was launched. The EU-funded project includes 40 partners from the manufacturing industries, service providers, universities, R&D establishments and professional organizations [9]. The need for the UpWind project was to explore the design limits of upscaling. This was necessary, because a significant part of future installed wind power will be located offshore. With regard to the rising energy demand of the EU and the contemporaneous increase of the energy output of wind energy turbines, there will be two possibilities for the future: the development of new technologies, for example new innovative turbine concepts or new materials which are lighter and stronger, as well as the upscaling of wind turbine dimensions, wind farm capacities and required electrical infrastructure [8].

This was in relation to the plans of the European Commission published in October 2009 for the future use of renewable energy. The European energy demand should be covered with a total of 20 % wind energy in 2020, and with a total of 33 % in 2030. On closer examination the requirement of wind energy in 2020 is located at 265 GW, including 55 GW offshore capacity. In 2030 the requirement is forecasted at 400 GW, including 150 GW offshore capacity [8]. This could be a difficult problem, up to impossible task, because the electrical demand for example in Germany is currently (2016) covered with a total of only 11.9 % wind energy [10] and is lower when considering the whole EU. A good sign is, that the installed capacity in the EU has increased from 2005 to 2016 from 41 GW up to 154 GW [11]. Anyway, when looking at the numbers the sense of the UpWind project is underlined as well as the need for previous described research studies (Chapter 1) becomes clear.

The duration of the UpWind project was 60 months. In this time, the project team worked on 15 workpackages, e.g. the aerodynamics and aeroelastics, the rotor structures and materials or the control system. The focus of UpWind was on the wind turbine itself. The availability, transport, installation and other influences were mostly neglected, unless their consideration was necessary, e.g. to optimize the turbine configuration. The overriding aim was to examine the limits of upscaling, taking into account the LCoE [8]. The final report was published in March 2011. At this point, the results will not be discussed in more detail, but just in one sentence: A 20 MW turbine is feasible [8]. The corresponding turbine dimensions and structural data are given in Chapter 3. Because of the great success of the project, some aspects are followed up as part of the so-called INNWIND project. The objectives of this project are the high performance innovative design of 10 – 20 MW offshore wind turbines and hardware demonstrators of some of the critical components [12].

During the development of a 20 MW wind turbine, some basic upscaling laws and relations were used. These laws and relations are important for this thesis, too. Because of this, the following Chapter 2.4 explains the facts.

2.4 Upscaling

The upscaling of turbines is used to transfer a specific turbine configuration to any desired size, for example to any desired maximum rated power output or to any desired rotor diameter [5]. In principle, turbines can be upscaled (or downscaled) if enough design information is available. When performing upscaling, some laws have to be observed. Taking these laws into account, there are several relations, which are available for upscaling. In the following, the laws and the relations are presented and explained.

2.4.1 Upscaling laws

In order to perform a successful upscaling, three upscaling laws, or so-called similarity rules, have to be observed. These laws are called [5, 7]:

1. The tip speed ratio remains constant

The tip speed ratio is defined by the following equation [2, 7]:

$$\lambda = \frac{\omega_{Tip} \cdot R}{u_{\infty}} \tag{2.1}$$

On the basis of this equation, it can be concluded that the tip speed has to remain constant, assuming the wind speed is also constant (ambient conditions do not change). As a result, the entire tip speed ratio remains constant, too. With regard to the upscaling, it means that in case of a larger rotor diameter generated by the upscaling, the tip speed of the rotor has to be reduced in order to comply with this law [7].

2. The number of blades, the airfoil, and the blade material are the same

The number of blades as well as the airfoil and the blade material have a significant effect on the aerodynamic properties of the entire turbine. As a result, a simple and non-reasoned change of these parameters is not permitted before upscaling. Thus, for example, the transformation of a three-bladed turbine into a two-bladed one is a very complex process, which is not done by omitting a blade and the reposition of the other two blades. Furthermore, in addition to the aerodynamic properties, the component weights also change by changing the airfoil and the blade material. As a result, the stresses on the blades as well as on the entire structure change, too [5]. For this reason, it is useful to reflect the airfoil and the blade material in detail within the concept design and, if necessary, to adapt the design. In this way the design can be improved.

3. Geometric similarity is maintained as far as possible

This law means, that all necessary parameters have to be upscaled according to the relations given in the next chapter. All further lengths and parameters are to be adapted appropriately, for example by using a standardized factor, so-called “q”. This factor presents the scale dependence for all the further lengths and parameters [7]. It can be chosen in theory arbitrarily, but should be useful chosen in practice. When comparing the starting turbine and the upscaled turbine, no major geometric differences should be recognizable.

2.4.2 Upscaling relations

The parameters of a starting turbine are adapted (upscaled) in accordance to different so-called upscaling relations. The basis of the upscaling relations is given by the rotor radius R. This means that if the ratio of the rotor radius between the starting turbine and the upscaled turbine is known, all other parameters can also be upscaled [2, 5, 7]. Table 03 shows an extract of the most important relations of the turbine parameters with respect to the rotor radius R. Further relations exist, but due to the large number of different parameters, it is almost impossible to summarize all relations in tabular form. For this reason, the table is limited.

Class	Parameter	Relation	Scale dependence
Power, forces, moments	Power	$\frac{P_1}{P_2} = \left(\frac{R_1}{R_2}\right)^2$	$\sim R^2$
	Torque	$\frac{Q_1}{Q_2} = \left(\frac{R_1}{R_2}\right)^3$	$\sim R^3$
	Thrust	$\frac{T_1}{T_2} = \left(\frac{R_1}{R_2}\right)^2$	$\sim R^2$
	Rotational speed	$\frac{\Omega_1}{\Omega_2} = \left(\frac{R_1}{R_2}\right)^{-1}$	$\sim R^{-1}$
	Weight	$\frac{W_1}{W_2} = \left(\frac{R_1}{R_2}\right)^3$	$\sim R^3$
	Aerodynamic moments	$\frac{M_{A,1}}{M_{A,2}} = \left(\frac{R_1}{R_2}\right)^3$	$\sim R^3$
	Static moments	$\frac{M_{S,1}}{M_{S,2}} = \left(\frac{R_1}{R_2}\right)^4$	$\sim R^4$
	Centrifugal forces	$\frac{F_{c,1}}{F_{c,2}} = \left(\frac{R_1}{R_2}\right)^2$	$\sim R^2$
	Drag forces	$\frac{F_{D,1}}{F_{D,2}} = \left(\frac{R_1}{R_2}\right)^2$	$\sim R^2$
	Inertia	$\frac{I_1}{I_2} = \left(\frac{R_1}{R_2}\right)^5$	$\sim R^5$

Table 03: Upscaling relations, part 1/2, (based on [2, 5, 7])

Class	Parameter	Relation	Scale dependence
Stresses	Aerodynamic	$\frac{\sigma_{A,1}}{\sigma_{A,2}} = 1 = \left(\frac{R_1}{R_2}\right)^0$	$\sim R^0$
	Gravitational	$\frac{\sigma_{g,1}}{\sigma_{g,2}} = \left(\frac{R_1}{R_2}\right)^1$	$\sim R^1$
	Centrifugal	$\frac{\sigma_{c,1}}{\sigma_{c,2}} = 1 = \left(\frac{R_1}{R_2}\right)^0$	$\sim R^0$
Resonances	Natural frequency	$\frac{\omega_{n,1}}{\omega_{n,2}} = \left(\frac{R_1}{R_2}\right)^{-1}$	$\sim R^{-1}$
	Excitation	$\frac{(\Omega_1/\omega_{1,n})}{(\Omega_2/\omega_{2,n})} = 1 = \left(\frac{R_1}{R_2}\right)^0$	$\sim R^0$

Table 03: Upscaling relations, part 2/2, (based on [2, 5, 7])

2.4.2.1 Basic equation: Square-cube law

As shown in Table 03, the power increases quadratic to the size of the rotor radius and the mass (weight) increases cubic to the size of the rotor radius [5, 13, 14]. This relation is called "Square-cube law" and can be explained by Figure 02 easily.

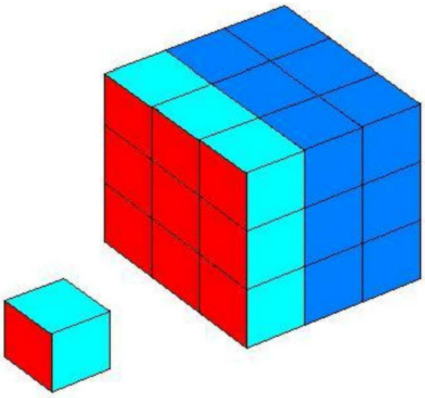

Figure 02: Square-cube law, (Source: [13])

Important for the realization of a wind turbine is that the costs relate to the mass of material [14]. This relationship has to be considered as negative, because as a result an upscaling limit exists. On a closer look, there are even two limits: first, the investment costs or so-called Capital Expenditures (CAPEX). If the costs are too high, the turbine is unprofitable and because of this no one would build it.

Second, the material weights itself. To achieve a certain stiffness of the turbine system, plenty of material is needed. However, a lot of material also results in an increase of weight, which again affects the stiffness. As a consequence, the upscaling is limited by the parameters and properties of the materials, which are used nowadays (2017).

2.4.2.2 Class “Power, forces, moments”

The relations of the class “Power, forces, moments” are basic relations, based for example on the square-cube law, which was explained before. For this reason, the relations are not to be explained in detail. The relations of the classes “Stresses” and “Resonances” can be deduced from the basic relations. To understand how it works, these relations are looked at closer in the following.

2.4.2.3 Class “Stresses”

In principle the aerodynamic stresses, the gravitational stresses and the centrifugal stresses are functions of the area moment of inertia and the applied moments. When looking at the aerodynamic stresses of the blade first, it is [5]:

$$\sigma_A = \frac{M_A \cdot y}{I} \tag{2.2}$$

The value y represents the distance to the neutral axis of the blade. In this context the distance is given by the thickness of the blade t. Furthermore, the inertia is calculated by taking the blade width c and thickness t into consideration:

$$y = \frac{t}{2} \tag{2.3}$$

$$I = \frac{c \cdot t^3}{12} \tag{2.4}$$

Thus, the aerodynamic stresses of the blade are [5]:

$$\sigma_A = \frac{M_A}{c \cdot t^2/6} \tag{2.5}$$

The aerodynamic moments have a scale dependence of ~ R^3 (compare Table 03). Both other parameters (width c and thickness t) have a scale dependence of ~ R^1, according to the upscaling law number 3, to maintain the geometric similarity as far as possible. As a consequence, the aerodynamic stresses are unchanged by upscaling (scale dependence ~ R^0).

Second, the gravitational stresses can be deduced in accordance to Equation 2.2. It is [5]:

$$\sigma_g = \frac{M_g \cdot y}{I} \tag{2.6}$$

The gravitational moment M_g is calculated by the weight of the blade W_{Blade} and the distance to the center of gravity L_{CoG}. For the distance to the neutral axis of the blade y in this case the blade width c is the decisive factor.

$$M_g = W_{Blade} \cdot L_{CoG} \tag{2.7}$$

$$y = \frac{c}{2} \tag{2.8}$$

For the inertia, the Equation 2.4 remains unchanged. Considering the Equations 2.6 to 2.8 before, the gravitational stresses of the blade can be calculated by [5]:

$$\sigma_g = \frac{W_{Blade} \cdot L_{CoG}}{t \cdot c^2/6} \tag{2.9}$$

When looking at this equation only the weight W_{Blade} increases cubic to the radius (scale dependence ~ R^3). All other parameters increase linear to the radius, similar to Equation 2.5. Thus, it can be concluded, that the gravitational stresses increase in proportion of the radius, too (scale dependence ~ R^1).

Finally, the equation of stresses due to centrifugal force can be calculated by [5]:

$$\sigma_g = \frac{(W/g) \cdot L_{CoG} \cdot \Omega^2}{A_c} \tag{2.10}$$

Whereby the centrifugal force is given by [5]:

$$F_c = \frac{W}{g} \cdot L_{CoG} \cdot \Omega^2 \tag{2.11}$$

So the weight again has a scale dependence of ~ R^3. The rotational speed is to be upscaled according to ~ R^{-1} (compare Table 03) and the area increases quadratic to the rotor radius. As a result, the centrifugal stresses are unchanged by upscaling (scale dependence ~ R^0), like the aerodynamic stresses described above.

2.4.2.4 Class “Resonances”

For the relations natural frequency and excitation of the class “Resonances” the scale dependences are to be demonstrated in a similar way. For this reason, they were omitted at this point. If necessary, profound explanations can be found for example within [5].

2.4.3 Current scientific literature and scaling trends

When looking at the upscaling of wind turbines, the relations of Table 03 are of theoretical nature, based on some basic mathematic equations. Because of this the applicability of the upscaling relations for the further work is to be critically regarded under consideration of the real behavior of the relations, which can be seen on the actual development (scaling trends) of the parameters. The relations of Table 03 are not in any way wrong. But the possibility is given, to improve the concept of an upscaled turbine, when considering newest scientific knowledge of technology. For this reason, the potentials need to be worked out and to be analyzed. All functions are based on historical trends. The data is totally “real world” (based on real turbines) and is in no way simplistic [15].

2.4.3.1 Blade mass

Although the square-cube law is a basic equation, other relations can be observed in reality. When looking, for example, at the cubic relation of the blade mass (blade weight) the development of turbines from the last 30 years has shown a scale dependence of approximately ~ $R^{2.3}$ instead of ~ R^3 [13, 14, 16]. Figure 03 presents this fact.

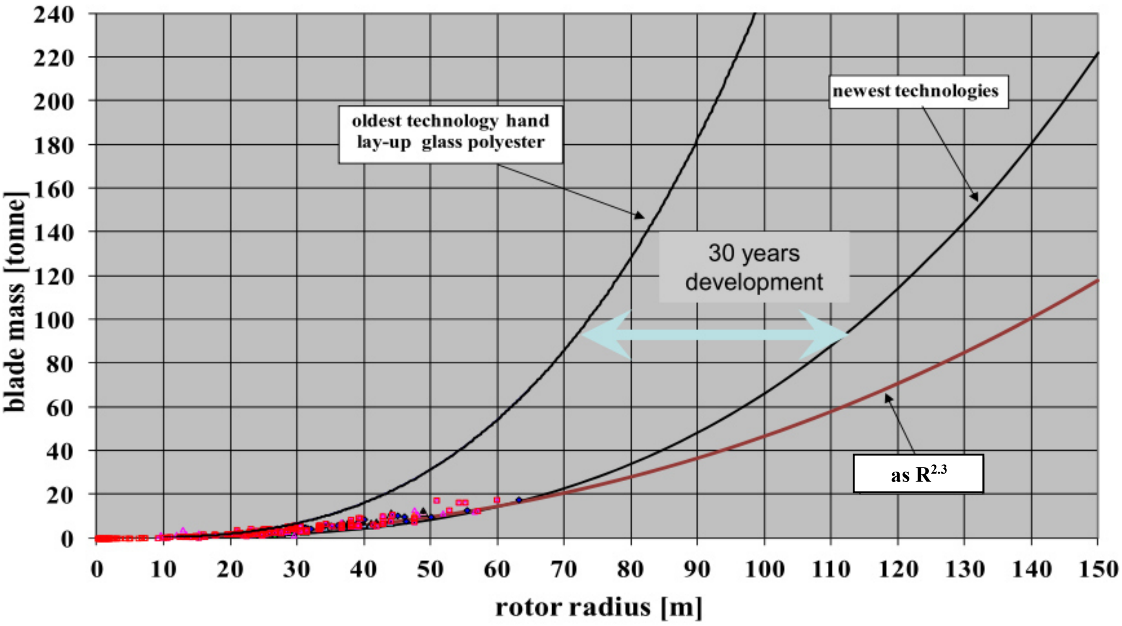

Figure 03: Relation of mass and rotor radius, (based on [13])

The figure shows different installations of the last 30 years (rotor radius plotted on x-axis and corresponding blade mass plotted on y-axis). All entries are combined to a trend line, which shows the scale dependence of ~ $R^{2.3}$. This is a positive progress, because it is a cost advantage as well as an increase of the upscaling limit (due to the changed proportionality factor, the upscaling limit is reached only by a larger rotor). It can be attributed among others to the use of materials with "better" properties (e.g. material with higher stiffness and simultaneously lower weight).

2.4.3.2 Nacelle mass

On the other hand, the nacelle mass corresponds to a scale dependence of ~ R^3 in reality, like the theoretical value of the square-cube law. This fact is true for turbines with a rotor diameter of at least 80 meters [14, 16]. It can also be shown when plotting various turbines of the last 30 years within a diagram and when identifying the corresponding trend line. The diagram can be found in the appendix (Figure A-01). When considering further turbines with a rotor diameter of at least 20 meters, the scale dependence is approximately ~ $R^{1.8}$ [14], but this is not realistic in respect to today's installations, because modern installations become larger and larger in rotor diameter. In general, it is to be noted, that the nacelle mass depends on its components. The nacelle mass is lower, when for example the converter is placed on the tower base instead of in the nacelle. Such aspects were negatively neglected in the context of this analysis of the nacelle mass [15].

2.4.3.3 Tower top mass

When considering the tower top mass, meaning the whole mass of the rotor (three blades plus hub) and the nacelle, a scale dependence of approximately ~ $R^{2.8}$ is to be determined. This fact is again true for turbines with rotor diameters above 80 meters. For turbines with a smaller rotor, the theoretical cubic relation of the square-cube law (scale dependence ~ R^3) is in line with reality [14].

2.4.3.4 Tower mass

The tower mass shows again a deviation of the scare-cube law. In principle, there is a big variation in tower design, because of the site conditions for example. So, on the one hand onshore installations have high towers and big rotor diameters in order to compensate interferences in wind flow due to the roughness of the ground (trees, buildings, etc.). On the other hand, offshore installations often have towers that are as low as possible, because there are fewer benefits of higher towers offshore. Because of this, there is a big scatter in tower mass, so it is reasonable to normalize the tower mass to rotor diameter (or to rotor radius, the result would be the same). The method of normalizing is used to reduce data scatter and to identify trends. When this has been done, a scale dependence of ~ $R^{2.6}$ can be found. This is true, when considering all normalized turbines [14]. The fact can be shown again by a diagram, which is attached to this thesis (Figure A-03). When looking at large onshore turbines in detail, the cubic relation based on the square-cube law (scale dependence ~ R^3) is right [14]. Thus, it is a reasoned assumption that the scale dependence for offshore turbines in detail is lower than ~ $R^{2.6}$. The main reason for this assumption is again the low tower height of offshore turbines. But in respect to this, no profound considerations have been made yet. Because of this, within the concept design (Chapter 5.2) the scale dependence of (exactly) ~ $R^{2.6}$ is to be looked in more detail.

2.4.3.5 Tower base moments

Following the same procedure as for the different masses, which are looked at closer before, for the tower base moments also other relations can be observed in reality, instead of the theoretical scale dependence of ~ R^3. As explained in Chapter 2.4.2.2, this scale dependence represents a basic relation, because of which a detailed description was omitted. For the analysis of the historical trends, all load calculations are considered, which were performed on basis of the GL or IEC standards[2] [15]. The results are different, according to the respective component. For the tower base roll moment M_x the dependence is approximately ~ $R^{3.2}$, for the tower base pitch moment M_y it is ~ $R^{2.3}$ and for the tower base yaw moment M_z a dependence of ~ R^4 could be found [15]. The deviation between the theoretical and practical scale dependence of the tower base yaw moment M_z caused by turbulences on the rotor [15]. When anticipating further work, these results are of slightly relevance, so that the corresponding diagrams are omitted here. This is, because in the course of the work insufficient information of load

---

[2] The GL (Germanischer Lloyd) and the IEC (International Electrotechnical Commission) provide standards and directives for load calculation for wind turbines. In detail, the GL (today DNV GL) provides classification, technical assurance, software and independent expert advisory services to the energy industry. The IEC provides international standards and conforming assessment for all electrical, electronic and related technologies [45, 46].

calculation of the considered turbines will be available. But, for the sake of completeness, the diagrams are shown in the appendix (Figures A-04 to A-06).

2.4.3.6 Blade root moments

The investigation of the trends of the blade root moments was also based on load calculations according to the GL and IEC standards. The analysis results in a scale dependence of $\sim R^{3.2}$ for the blade root roll moment M_x, a scale dependence of $\sim R^{2.8}$ for the blade root pitch moment M_y and for the blade root yaw moment M_z a dependence of $\sim R^{2.7}$ [15]. Again the results are of slightly relevance for the further work, for the same reasons as described before. The diagrams are attached to this thesis, too (Figures A-07 to A-09).

2.4.3.7 Summary

Finally, the Table 04 summarizes the results from the current scientific knowledge.

Parameter	Scale dependence based on classical upscaling	Scale dependence based on historical trends
Blade mass (weight)*	$\sim R^3$	$\sim R^{2.3}$
Nacelle mass (weight)*	$\sim R^3$	$\sim R^3$
Tower top mass (weight)*	$\sim R^3$	$\sim R^{2.8}$
Tower mass (weight)*	$\sim R^3$	$\sim R^{2.6}$
Tower base roll moment M_x*	$\sim R^3$	$\sim R^{3.2}$
Tower base pitch moment M_y*	$\sim R^3$	$\sim R^{2.3}$
Tower base yaw moment M_z*	$\sim R^3$	$\sim R^4$
Blade root roll moment M_x*	$\sim R^3$	$\sim R^{3.2}$
Blade root pitch moment M_y*	$\sim R^3$	$\sim R^{2.8}$
Blade root yaw moment M_z*	$\sim R^3$	$\sim R^{2.7}$
*Only valid under consideration of the restrictions and basic conditions, which are described in the chapters before.		

Table 04: Results from current scientific knowledge

2.4.3.8 Critical review on current scientific literature

First of all, it has to be noted that the data, which was considered within this chapter ([13], [14], [15] and [16]), do not show any information about possible uncertainties. There is no information given which data is included into the diagrams and which data was omitted. What is also neglected in all studies is the underlying technology of the turbine, meaning among others the blade material, the drive train concept, the design style (concepts and operational characteristics) and the side conditions (e.g. IEC class I or class II turbine) [15]. In principle, the grow of turbine size depends on the technology (respectively on time) and not on the diameter itself. Furthermore, the diameter corresponds to the technology, too. For this reason, at this point, the reasonableness of an “all-data” description within a diagram is to be questioned. The situation is similar, when considering the trend lines. There is no information given which data is used to generate the trend lines and which technology the turbines consist of. This means, it is easy to modify the slope by adding or omitting data. Consequently, all data and all trend lines depend on the perception (or preoccupation) of the respective scientific studies. Overall, it is difficult to differentiate between real scaling trends and effects of technology improvements [15]. For this reason, the relations are looked at critically in view of the upcoming upscaling process as well as the concept design.

Chapter 3

State of the Art three-bladed wind turbines

From today's point of view several turbines could be called "State of the Art" turbines. In this chapter, some of these turbines are listed and described. A distinction is made between turbines for research purposes and turbines for the purpose of energy production (turbines, which are currently available on the market). The maximum rated power output is set to ≥ 10 MW for research turbines and to ≥ 8 MW for energy production turbines. Thus, the listed turbines are the largest of their kind. In the following, the listing takes place from large turbines to small ones. In addition to an introductory description, the technical data is presented in tabulated form.

3.1 Wind turbines for research purposes

Turbines for research purposes are systems developed on paper to answer different scientific questions. In most cases, it is not planned to build real-scaled prototypes of the turbines. But sometimes it is necessary, depending on the project, to build prototypes during the project or following the completion of a project. However, in general research turbines are of theoretical nature, like the related research projects in which the turbines are developed. By means of a comprehensive literature research, three turbines were identified from research projects, which are relevant for the present work. All turbines have a maximum rated power output of at least 10 MW.

3.1.1 UpWind 20 MW Wind Turbine

The „UpWind 20 MW Wind Turbine“, or briefly „UpWind Turbine“, is an upscaled turbine based on a 5 MW reference turbine. The upscaling as well as the concept design were realized within the UpWind project, whose content was described before in the form of a project overview. The upscaling process was performed according to the laws and relations of Chapter 2.4. The so-called “IEA reference turbine (version 8)”, which was developed by the National Renewable Energy Laboratory (NREL) [17, 18], was used as a 5 MW reference turbine. This turbine was first upscaled to a 10 MW turbine, because first commercial 10 MW turbines were developed at the time of the project (2006 – 2011) [8]. This was followed by the upscaling to a 20 MW turbine. Within the project, it soon became clear that the resulting turbine (based on classical upscaling) was not a suitable one. The system was uneconomical and impossible to manufacture. As weak points, the weight on top of the tower, the loads on the entire structure as well as the aerodynamics of the rotor blades and their control (rotor blade control) were determined [8]. For this reason, the “UpWind 20 MW Wind Turbine” was developed step by step during the entire project. The existing turbine configuration has been continually improved and optimized. For example, the design tools of the “FOCUS6” program[3] were used for aerodynamics and structural blade design [17].

Overall, the following steps have been taken place within the UpWind project with regard to the upscaling as well as the design of the 20 MW turbine:

- Step 1: Formulation of the basic design conditions,
- Step 2: Use of classical similarity laws (upscaling),

---

[3] “FOCUS6” is an integrated modular wind turbine design tool, mainly developed by the Knowledge Centre Wind turbine Materials and Constructions (WMC). Some modules are developed with contributions of the Energy research Centre of the Netherlands (ECN) [47].

- Step 3: Design improvements (use of “FOCUS6” design tools),
    - Aerodynamic blade design (ECN-Tool),
    - Structural blade design (WMC-Tool),
- Step 4: Controller design,
- Step 5: Load set calculations [17].

This approach creates a system that was smart, reliable, accessible, efficient and lightweight [8]. Table 05 shows some parts of the technical specification. An overview of all technical specifications (e.g. blade geometry, generator properties, inertia and torque information, etc.) has been omitted here. For the sake of completeness, it can be found in the appendix (Table A-01) or can be extracted directly from [17].

UpWind 20 MW Wind Turbine

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	20 MW
	Wind regime	IEC class	IEC class IB
	Cut-in wind speed	$v_{cut\text{-}in}$	unknown
	Nominal power output at	v_{rated}	10 m/s
	Cut-out wind speed	$v_{cut\text{-}out}$	25 m/s (reasoned assumption)
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	252 m
	Swept area	A_{Rotor}	49,850 m^2
	Power regulation	-	Variable speed, pitch control
	Rotor tilt angle	α	5 deg
	Maximum rotor speed	Ω_{MAX}	6.05 rpm
	Maximum tip speed	v_{Tip}	80 m/s
	Rotor mass (hub + blades)	W_{Rotor}	770 t
Blade	Blade span	L_{Span}	123 m
	Blade cone angle	β	- 2.5 deg
	Blade prebend	$L_{Prebend}$	Existing, but unknown
	Aerodynamic profile	-	NACA, DU, Cylinder
	Blade material	-	Glass fiber reinforced plastic (GRP)
Hub, Nacelle, Tower	Hub height	H_{Hub}	153 m
	Tower top mass (nacelle + rotor)	W_{Top}	1,920 t + 770 t
	Tower mass	W_{Tower}	2,780 t
Drive train	Gearbox type	-	Existing, but unknown
	Generator type	-	Permanent Magnet Transverse Flux Generator, *optional:* other

Table 05: Technical specifications UpWind 20 MW Wind Turbine, extract, (based on [8, 17])

The Figures 04 explains some of the relevant geometric turbine parameters.

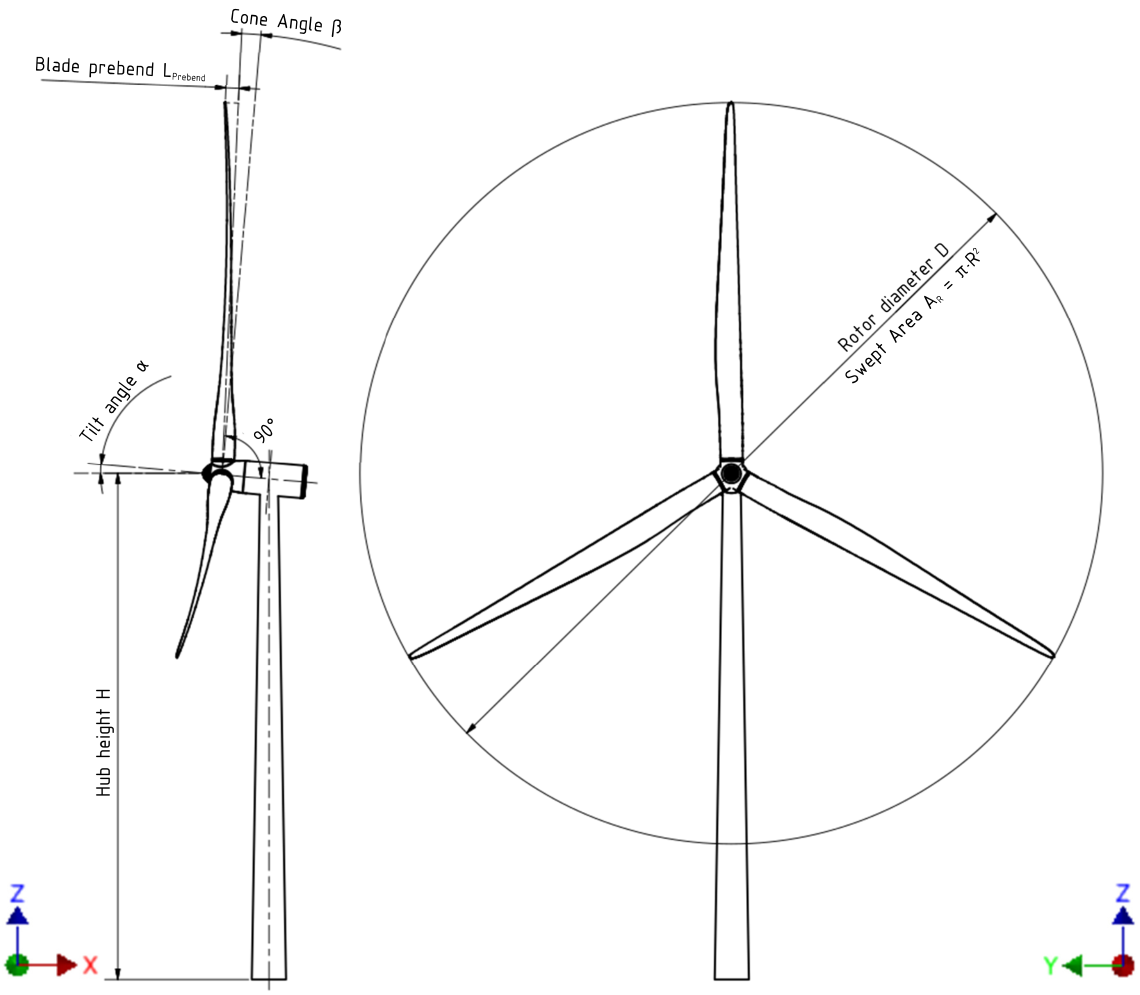

Figure 04: Geometric turbine parameters

Subsequently, Figure 05 explains the geometric blade parameters in detail:

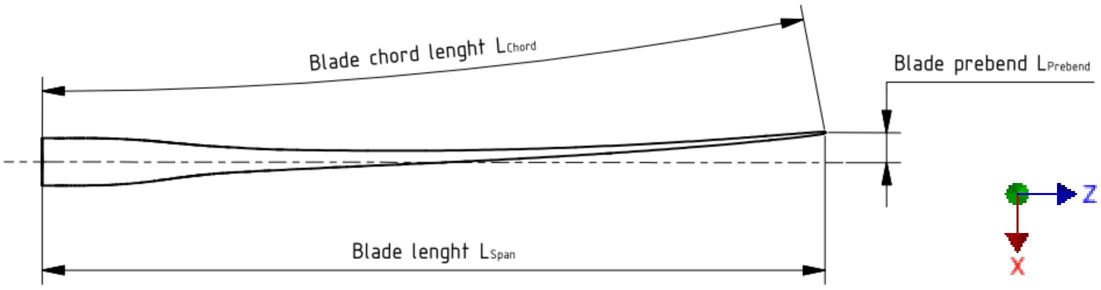

Figure 05: Geometric blade parameters

In order to achieve the design shown above, several problems had to be overcome within the UpWind project. For example, the aerodynamic coefficients had to be determined for higher Reynolds numbers. This is because the local chord values of the blades are larger in the upscaled case than in the starting case (5 MW reference turbine), which increases the operational Reynolds numbers of the blade sections (assuming that the tip speed and the compressibility are constant during upscaling). The Reynolds numbers are important for the aerodynamic performance of the blades and no investigations on such large blades have been performed in the past. When looking again at the rotor blades, there was also the risk of buckling (respectively kinking), which is due to the extreme length of 123 m. With regard to the weight, the stiffness of the blade was too low. This problem was solved by adding a stiffening in the form of an additional shear web (fiber layer). Thereby, the mass of the blades negatively increased. For the controller, completely new strategies had to be developed, because the control of such large systems with conventional controllers was simply not possible. One reason for this is that the eigenfrequencies (natural frequencies) of the tower are important for the controller design [17]. This is because the controller is not allowed to begin to oscillate the tower, for example due to oscillation of the blades during pitching. In respect to this, the effect of an individual pitch control (IPC) was also investigated. Field tests demonstrates, that the fatigue loads can be reduced by 20 – 30 % with an individual pitch control, compared to a homogeneous pitch control [8]. In consequence of this, an IPC shows high potentials to reduce material and to that effect also costs, because lower loads result in the possibility of use of lighter components.

Finally, it can be register that the UpWind project was a very important step for the development of future wind turbines. The project shows, that a 20 MW turbine is feasible, if some key innovations (e.g. an addition fiber layer (fiber composite material) of the blades and a new controller design) are integrated. In principle, there were no significant problems when upscaling to this 20 MW turbine [8]. All results are based mainly on theoretical considerations and calculations. As a consequence, some parameters have to be considered for practical applications. For example, a practical determination of the real airfoil (selection and thickness) is indispensable [17]. With regard to the LCoE, the

UpWind project showed that it is possible to realize such large installations without cost increases, provided that the practical material costs do not exceed the theoretically assumed values [8].

3.1.2 Azimut Offshore Wind Energy 15 MW wind turbine

Within the Azimut Offshore Wind Energy 2020 project the development of a 15 MW offshore wind turbine was under investigation. The leading coordinator of the project was Gamesa, which has been merged with Siemens in 2017 [19]. Overall, eleven Spanish companies and 22 research centers were involved. The duration was four years, ending in December 2013. The aim of the project was to enable the development of the world's largest capacity wind turbine by 2020. Another aim was to generate necessary knowledge as well as to overcome technical and economic barriers during the development process of the turbine [20, 21].

Finally, the project was successfully completed. All project partners developed together for example new technologies, new materials for blade design, new testing processes and models [21]. The final result of the project was not a complete 15 MW wind turbine with all its components, but a lot of key technologies for the future development of high capacity wind turbines were generated. Unfortunately, most of the details are not public available. For this reason, it is not possible to give a tabular summary of the technical specifications. However, many of the key technologies, which were found, are described in [21]. Because the technical specifications are of primary relevance for this work, a compilation of the key technologies has been omitted.

3.1.3 DTU 10 MW Reference Turbine

The "DTU 10 MW Reference Wind Turbine" or briefly „DTU 10 MW Turbine“ was designed for the so-called "Light Rotor project" of the Technical University of Denmark (DTU). The project was realized from October 2010 to May 2014. Within the project the aims were to create the design basis for next-generation wind turbines of 10+ MW [22]. The project focused on the rotor, although the rotor is only a small fraction of the entire costs. This focus was chosen because the rotor is the key component of a wind turbine and characterizes the Annual Energy Production (AEP) [23].

Within the project a reference turbine was needed, to compare different designs. Therefore, an integrated design process was created and used. This design process consists of the aerodynamic design, the aeroelastic design and the structural design in a closed loop (iteration process) [23]. It was realized after the simple upscaling of the same turbine, which was used within the UpWind project (IEA 5 MW reference turbine). At this point, a detailed description of the design process has been omitted. If necessary, more detailed information on the design process can be found, for example in [23]. What is important at this point is that the DTU 10 MW Turbine is not the result of a simple upscaling, but the result of a well-conceived and protracted design process. The Table 06 summarizes the results. Again only some parts of the technical specification are shown. An overview of the complete technical specification is attached (Table A-02).

DTU 10 MW Reference Turbine

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	10 MW
	Wind regime	IEC class	IEC class IA
	Cut-in wind speed	v_{cut-in}	4 m/s
	Nominal power output at	v_{rated}	11.4 m/s
	Cut-out wind speed	$v_{cut-out}$	25 m/s
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	178.3 m
	Swept area	A_{Rotor}	24,950 m^2
	Power regulation	-	Variable speed, pitch control
	Rotor tilt angle	α	5 deg
	Maximum rotor speed	Ω_{MAX}	9.6 rpm
	Maximum tip speed	v_{Tip}	90 m/s
	Rotor mass (hub + blades)	W_{Rotor}	230.6 t (hub of 105.5 t + 3 blades of 41.7 t)
Blade	Blade span	L_{Span}	≈ 86.35 m
	Blade cone angle	β	- 2.5 deg
	Blade prebend	$L_{Prebend}$	3.332 m
	Aerodynamic profile	-	FFA-W3-XXX, Cylinder
	Blade material	-	Glass fiber reinforced plastic (GRP) (reasoned assumption)

Table 06: Technical specifications DTU 10 MW Reference Turbine, extract, part 1/2, (based on [22, 24])

DTU 10 MW Reference Turbine

Class	Parameter	Symbol	Characteristic
Hub, Nacelle, Tower	Hub height	H_{Hub}	119 m
	Tower top mass (nacelle + rotor)	W_{Top}	446.0 t + 230.6 t
	Tower mass	W_{Tower}	628.4 t
Drive train	Gearbox type	-	Multiple-stage gearbox
	Generator type	-	Permanent magnet synchronous generator (PMG)

Table 06: Technical specifications DTU 10 MW Reference Turbine, extract, part 2/2, (based on [22, 24])

The final design with the parameters shown in the table above has overall a good aerodynamic performance and a fairly low weight [22, 23, 24]. It is public available and a representative basis for next generation of new optimized rotors. All information (again aerodynamic, aeroelastic and structural design) can be downloaded for free after registration. This includes all model- and simulation data, which were created during the duration of the project.

3.2 Wind turbines for energy production purposes

Turbines for the purpose of energy production are systems developed by companies to be sold to wind park and turbine operators, for example to energy production companies. Some of the systems listed below can already be ordered from the respective turbine manufactures. For other turbines, there is only one build prototype available or a prototype is just even planned.

3.2.1 AMSC wt10000dd SeaTitan^{TM}

The SeaTitan^{TM} 10 MW wind turbine of type “wt10000dd” is a wind turbine model developed by AMSC American Superconductor. The design is based on a lighter weight and highly reliable direct drive to guarantee a perfect fit for offshore conditions. By using a Superconductor generator, tolerances and deformation criteria can be eliminated. The Superconductor generator is significantly smaller and lighter than a generator using conventional technologies [25]. This can be an advantage when a lightweight construction is desired. The technical specifications of the turbine model are listed in Table 07.

AMSC wt10000dd SeaTitan™

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	10 MW
	Wind regime	IEC class	/
	Cut-in wind speed	$v_{\text{cut-in}}$	4 m/s
	Nominal power output at	v_{rated}	11.5 m/s
	Cut-out wind speed	$v_{\text{cut-out}}$	30 m/s
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	190 m
	Swept area	A_{Rotor}	28,350 m^2
	Power regulation	-	/
	Rotor tilt angle	α	/
	Maximum rotor speed	Ω_{MAX}	10 rpm
	Maximum tip speed	v_{Tip}	99 m/s
	Rotor mass (hub + blades)	W_{Rotor}	/
Blade	Blade span	L_{Span}	/
	Blade cone angle	β	/
	Blade prebend	L_{Prebend}	/
	Aerodynamic profile	-	/
	Blade material	-	/
Hub, Nacelle, Tower	Hub height	H_{Hub}	125 m
	Tower top mass (nacelle + rotor)	W_{Top}	/
	Tower mass	W_{Tower}	/
Drive train	Gearbox type	-	Direct drive
	Generator type	-	High-Temperature Superconducting synchronous generator (HTS synchronous)

Table 07: Technical specification AMSC wt10000 SeaTitan™, (based on [25, 26])

The turbine is not manufactured by AMSC American Superconductor, but can be taken and manufactured under license from qualified companies around the world [25]. The turbine has not been manufactured yet and there is also no prototype build [26].

3.2.2 MHI Vestas Offshore V164-9.0 MW

The wind turbine of type V164-9.0 MW from MHI Vestas Offshore Wind is the prototype of a new offshore turbine with a maximum rated power output of 9 MW. MHI Vestas Offshore was founded in April 2014 and is a subsidiary of Vestas Wind Systems A/S and Mitsubishi Heavy Industries Ltd. [27]. Both companies have many years of experience in offshore wind energy and have profiled themselves in the global market. The turbine of type V164-9.0 MW is a successor of the turbine of type V164-8.0 MW (see Figure 06).

Figure 06: MHI Vestas Offshore V164-8.0 MW, (Source: MHI Vestas Offshore Wind; available from: http://www.mhivestasoffshore.com/innovations/)

Structurally and geometrically, both systems are the same. By upgrading the drive train, mainly the generator, the higher rated power output is obtained [28, 29]. Table 08 shows the technical specifications.

MHI Vestas Offshore V164-9.0 MW

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	9 MW
	Wind regime	IEC class	IEC class S
	Cut-in wind speed	v_{cut-in}	4 m/s (reasoned assumption)
	Nominal power output at	v_{rated}	13 m/s (reasoned assumption)
	Cut-out wind speed	$v_{cut-out}$	25 m/s (reasoned assumption)

Table 08: Technical specifications MHI Vestas Offshore V164-9.0 MW, part 1/2, (based on [28, 29])

MHI Vestas Offshore V164-9.0 MW			
Class	**Parameter**	**Symbol**	**Characteristic**
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	164 m
	Swept area	A_{Rotor}	21,100 m^2
	Power regulation	-	/
	Rotor tilt angle	α	/
	Maximum rotor speed	Ω_{MAX}	12.1 rpm
	Maximum tip speed	v_{Tip}	104 m/s
	Rotor mass (hub + blades)	W_{Rotor}	3 blades of 35 t + unknown hub weight
Blade	Blade span	L_{Span}	/
	Blade cone angle	β	/
	Blade prebend	$L_{Prebend}$	/
	Aerodynamic profile	-	/
	Blade material	-	/
Hub, Nacelle, Tower	Hub height	H_{Hub}	105 / 140 m
	Tower top mass (nacelle + rotor)	W_{Top}	390 t + rotor weight
	Tower mass	W_{Tower}	/
Drive train	Gearbox type	-	Planetary drive
	Generator type	-	Permanent magnet synchronous generator (PMG)

Table 08: Technical specifications MHI Vestas Offshore V164-9.0 MW, part 2/2, (based on [28, 29])

The turbine with the previously described specifications is not yet available on the market, but a prototype has already been installed in the Østerild wind turbine test field, Denmark [29].

3.2.3 Siemens Wind Turbine SWT-8.0-154

The Siemens Wind Turbine of the type SWT-8.0-154 is an offshore turbine with a maximum rated power output of 8 MW [30]. The turbine has been developed by the Siemens AG, respectively its Wind Power and Renewables Division (since 2017 Siemens Gamesa Renewable Energy [19]). The Siemens AG also carries out the production of this turbine. In principle, the turbine is based on the proven and optically identical 7 MW turbine of the type SWT-7.0-154 [31]. This turbine is shown in Figure 07:

Figure 07: Siemens SWT-7.0-154, (Source: Siemens Wind Power; available from: https://www.siemens.com/press/IM2016020430WPEN)

By upgrading the components within the nacelle, the maximum rated power output increased to 8 MW, whereby the geometry stays the same. The key step of this upgrade was the implementation of a new magnet technology in the drive train of the directly driven turbine, that had a higher efficiency than the technology of the predecessor-turbine SWT-7.0-154. This allowed an increase of the maximum rated power output by more than 14 %, from 7 MW up to 8 MW. The rest of the turbine are the same proven technologies, for example the direct drive technology, the so-called IntegralBlade® technology[4], the hub and tower concepts, etc. [31]. The following Table 09 shows the technical specifications.

---

[4] The "IntegralBlade® technology" is a blade manufacturing method patented by Siemens Wind Power. The method allows to produce complete, seamless blades in a single process [48].

Siemens Wind Turbine SWT-8.0-154

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	8 MW
	Wind regime	IEC class	IEC class IB (IEC class S)
	Cut-in wind speed	$v_{\text{cut-in}}$	3 – 5 m/s
	Nominal power output at	v_{rated}	13 – 15 m/s
	Cut-out wind speed	$v_{\text{cut-out}}$	25 m/s
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	154 m
	Swept area	A_{Rotor}	18,600 m^2
	Power regulation	-	Variable speed, pitch control
	Rotor tilt angle	α	6 deg
	Maximum rotor speed	Ω_{MAX}	10.8 rpm
	Maximum tip speed	v_{Tip}	87 m/s
	Rotor mass (hub + blades)	W_{Rotor}	3 blades of 28 t + hub of 85 t
Blade	Blade span	L_{Span}	75 m
	Blade cone angle	β	/
	Blade prebend	L_{Prebend}	/
	Aerodynamic profile	-	Siemens proprietary airfoils, FFA-W3-XXX
	Blade material	-	Glass reinforced epoxy resin composite (GRE)
Hub, Nacelle, Tower	Hub height	H_{Hub}	Site-specific
	Tower top mass (nacelle + rotor)	W_{Top}	320 t + 169 t
	Tower mass	W_{Tower}	480 t (site specific)
Drive train	Gearbox type	-	Direct drive
	Generator type	-	Permanent magnet synchronous generator (PMG)

Table 09: Technical specifications Siemens Wind Turbine SWT-8.0-154, (based on [30, 32, 33])

Because the SWT-8.0-154 based, as already mentioned, on the proven predecessor-turbine SWT-7.0-154 the whole production process is clear and the supply chain already exists [31]. Overall, the Siemens AG has more than 30 years of experience in wind power, which is one of the reasons for providing simultaneous proven technologies and technical innovations. A prototype of the turbine was installed in January 2017 in the Østerild wind turbine test field, Denmark. The final type certification is planned for 2018.

3.2.4 Adwen AD 8-180

The so-called “Adwen AD 8-180” wind turbine, manufactured by ADWEN Offshore, S.L., is an offshore wind turbine with a maximum rated power output of 8 MW. The turbine is still in the development process (at the time of these thesis in prototype phase). The base of the turbine is the tried and tested 5 MW turbine of type “Adwen AD 5-132” [34]. But the turbine is not the product of simple upscaling. During the project a lot of assemblies and components have been created completely new. This includes the design, the development, the manufacturing and the validation of these components, for example the nacelle structure, the air conditioning system and the base tower opening [34]. The results of the R&D project (technical specifications) are shown in the table below.

Adwen AD 8-180

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	8 MW
	Wind regime	IEC class	IEC class IB
	Cut-in wind speed	$v_{cut\text{-}in}$	3 m/s
	Nominal power output at	v_{rated}	12 m/s
	Cut-out wind speed	$v_{cut\text{-}out}$	30 m/s
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	180 m
	Swept area	A_{Rotor}	25,425 m²
	Power regulation	-	Variable speed, pitch control
	Rotor tilt angle	α	/
	Maximum rotor speed	Ω_{MAX}	7.5 rpm
	Maximum tip speed	v_{Tip}	71 m/s
	Rotor mass (hub + blades)	W_{Rotor}	/
Blade	Blade span	L_{Span}	88.4 m
	Blade cone angle	β	/
	Blade prebend	$L_{Prebend}$	/
	Aerodynamic profile	-	/
	Blade material	-	/
Hub, Nacelle, Tower	Hub height	H_{Hub}	≈ 90 m (site specific and foundation concept)
	Tower top mass (nacelle + rotor)	W_{Top}	550 t
	Tower mass	W_{Tower}	/
Drive train	Gearbox type	-	Planetary gearbox
	Generator type	-	Permanent magnet synchronous generator (PMG)

Table 10: Technical specifications Adwen AD 8-180, (based on [34, 35])

As shown in the table, one rotor blade has the length of 88.4 meters. These blades are the longest blades in the world, which have ever been manufactured [36]. The blades are specifically designed for this turbine. Manufacturer is LM Wind Power in Denmark. Furthermore, the turbine has the world's biggest gearbox (2016). The two-stage-planetary gearbox, manufactured by Winergy, has a total weight of 86 tons and is the main component of the drive train [34]. Finally, Figure 08 presents the whole turbine.

Figure 08: Adwen AD 8-180, (Source: ADWEN;
available from: http://www.adwenoffshore.com/de/news-medias/multimedia-library/)

The first prototype of the turbine is going to be installed in Bremerhaven, Germany in 2017 [35]. The serial production is excepted in 2018. Turbines for three offshore wind parks in France have already been ordered [34].

3.3 Wind turbines (not classifiable or other purposes)

In the following, one turbine is listed, that is not classifiable. The purpose of this turbine is energy production as well, but the layout is different from today's state of the art turbines.

3.3.1 Sway Turbine ST 10

The so-called Sway Turbine ST 10 is a turbine concept developed by Sway Turbine AS over a period of seven years to 2012. Sway Turbine AS is a Norwegian technology company, that was founded in 2010, due to the demerge of Sway AS (founded in 2000) into two independent companies [37, 38]. The developed turbine has a maximum rated power output of 10 MW. The rotor diameter is 164 meters. Main component of the concept, and the difference to the state of the art turbines, is the usage of a generator with an ironless stator core within the drive train of the turbine [38, 39]. The concept is shown in Figure 09.

Figure 09: Sway Turbine ST 10, (Source: Sway Turbine AS; available from: http://www.swayturbine.no/?page=219)

The idea to use a stator core without iron was to reduce attracting forces between rotor and stator. By use of an ironless stator core there is no direct magnetic attraction between rotor and stator [40]. Furthermore, such a large generator reduces the magnet usage. Other benefits are a lighter generator and a cost advantage of approximately 20 % relative to a conventional direct drive generator. The aim of the whole concept was to reduce the total LCoE. The concept design of the turbine has shown, that a reduction of the LCoE was possible, by using this generator concept [38, 39]. Finally, there have been no commercial turbines as well as prototypes build up to now (2017). When looking at the future, it is questionable whether this will happen, because the latest updates on this turbine concept have already been carried out in 2012. There are no newer publications.

Chapter 4

Choice of turbine(s) for upscaling

After the description of the “State of the Art” turbines in the previous chapter, this chapter will focus on the evaluation and choice of a turbine (if applicable turbines) for upscaling.

4.1 Summary of possible turbines for upscaling

First of all, the Table 11 summarizes the turbines from Chapter 3, which are basically suitable for upscaling. In general, only turbines can be upscaled, of which the technical data, respectively the technical specifications are available. At this point there is no statement on the quality and the completeness of the given information. For easier handling of the turbines, they are numbered.

No.	Max. rated power output	Name	Purpose
1	20.0 MW	UpWind 20 MW Wind Turbine	Research purpose
2	10.0 MW	DTU 10 MW Reference Turbine	Research purpose
3	10.0 MW	AMSC wt10000dd SeaTitan™	Energy production purpose
4	9.0 MW	MHI Vestas Offshore V164-9.0 MW	Energy production purpose
5	8.0 MW	Siemens Wind Turbine SWT-8.0-154	Energy production purpose
6	8.0 MW	Adwen AD 8-180	Energy production purpose

Table 11: Summary of listed turbines

The turbine with the number 1 is the „UpWind 20 MW Wind Turbine“, which is to be used as reference turbine for the comparison of at least two 20 MW turbines in the further course of this work (Chapter 6). The turbine is already scaled to a maximum rated power output of 20 MW so the turbine does not have to be upscaled.

By omitting all turbines which are not relevant for upscaling, the turbines with the numbers 2 to 6 remain. From these turbines at least one is to be selected for upscaling. In order to make an objective selection, the quality and completeness of the technical data are evaluated in accordance to VDI 2225.

4.2 Evaluation of turbines

In order to find out which turbine (if applicable turbines) promises (promise) the greatest possible success, when upscaling in the course of this work, an evaluation according to VDI 2225 is carried out. In this standardized evaluation method, which is usually carried out on a form, the different varieties, in this case different turbines, are evaluated according to defined evaluation criteria with points. Therefore, useful criteria have to be defined in a first step.

4.2.1 Evaluation criteria

With regard to the technical specifications of the turbines and by means of a closer look on the turbines following criteria were defined:

4.2.1.1 Completeness

A very important criterion is given by the completeness of the tabled turbine data, which was described before. A successful upscaling of a turbine (Chapter 5) will only be possible, if sufficient technical data of the respective turbines is available. In regard to this, the lengths, the masses and other measures are of special importance. For this reason and with regard to the impending weighting of the evaluation criteria, a separate criterion is defined for each data-class (see Table 06 to 10). There are five criteria which are called:

- Completeness „Operational Data“
- Completeness „Rotor“
- Completeness „Blade“
- Completeness „Hub, Nacelle, Tower“
- Completeness „Drive Train“

Chapter 4.2.2 presents and explains the weighting of the criteria.

4.2.1.2 Possibility of teetering hub

An absolutely necessary evaluation criterion is described by the design of the hub. The hub should have the possibility to teeter, in other words it should be possible to design the hub as a so-called teetering hub. This is due to the fact that two-bladed wind turbines, as they are going to design in the upcoming research project (see Chapter 1), usually have teetering hubs to compensate adverse load situations. Two-bladed turbines are more susceptible to changing ambient conditions compared to three-bladed turbines [2]. Thus, the loads of a two-bladed turbines, for example, are strongly dependent on the three-dimensional irregularities of the wind (wind gradient), the oblique flow and the pitch angle. The use of teetering hubs can counteract this and can relieve the driveshaft of occurring bending stresses caused by the previous described influences [7]. Figure 10 shows the structure of a teetering hub. It is shown a hub of a downwind-turbine schematically.

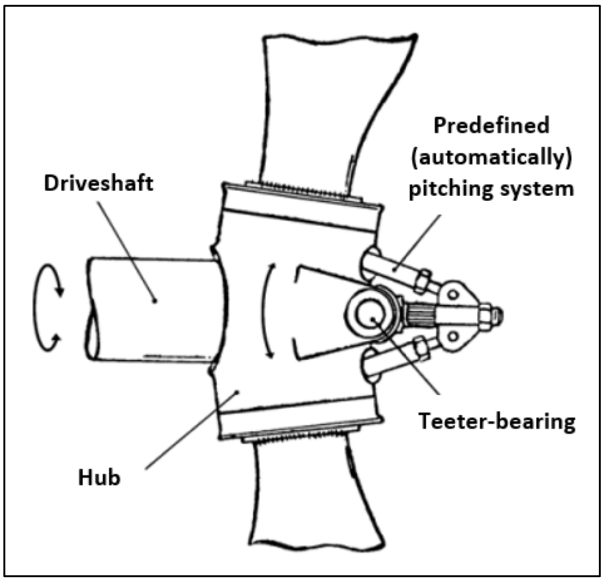

Figure 10: Teetering hub, (based on [2])

The most important component of the teetering hub is the so-called teeter-joint or teeter-bearing, about which axis the entire rotor is movable. It rotates with the rotor and is ideally located in the center of gravity of the rotor-hub assembly. The center of gravity depends on both the geometry of the rotor blades, meaning the tilt angle of the rotor, the cone angle and the prebend of the blades, as well as the ambient conditions, for example the inequality of the wind gradient [2, 7]. To limit the teeter movement, end fittings and dampers are integrated into the hub. These can be designed, for example, mechanically or hydraulically [2]. Furthermore, the teeter movement can be regulated by the predefined pitching of the blades (pitch teeter coupling). As shown in Figure 10, this is classically done by using a mechanical linkage. Nowadays, with regard to the advanced control technology, a regulation by the individual pitching of the blades (individual pitch control) is conceivable [2].

Teetering hubs can be used for downwind systems as well as for upwind systems, which are considered in this work. In principle, the concept of the drive train of the turbines is crucial for the technical feasibility of a teetering hub. In respect to this, eight drive train concepts can be distinguished [41]. The following list summarizes the concepts. Subsequently it is explained, for which concepts a teetering hub can theoretically be realized, or which restrictions are associated with an implementation. In respect to this, some schematic drawings of the concepts are shown. An overview of the schematic drawings of all concepts can be found in the appendix. In this context, examples of turbine manufactures, using the concepts, are shown, too (Figures A-10 to A-24).

Concepts with gearbox and generator:

- Concept 1: Detached drive train (Figure A-10 and A-11),
- Concept 2: Partial integrated drive train (Figure A-12 and A-13),
- Concept 3: Integrated drive train (*out of date*) (Figure A-14),
- Concept 4: Torque bearing (Figure A-15 and A-16),
- Concept 5: Bearings on kingpin (Figure A-17 and A-18).

Concepts with direct drive:

- Concept 6: Detached drive train with direct drive (Figure A-19 and A-20),
- Concept 7: Integrated drive train with direct drive (Figure A-21 and A-22),
- Concept 8: Bearings on kingpin with direct drive (Figure A-23 and A-24) [41].

For the gearbox concepts 1 to 4, the installation of a teetering hub is possible without restrictions. The concepts have a free end on the driveshaft in the hub, whereby a teeter-bearing can be integrated without any additional construction effort. The concepts have minor structural changes. If necessary, the corresponding illustrations can be found in the appendix (Figures A-10 to A-16).

In contrast, the concept 5 is different. The integration of the bearings into the hub does not seem to make a teeter movement possible. In order to follow this, Figure 11 presents the concept 5.

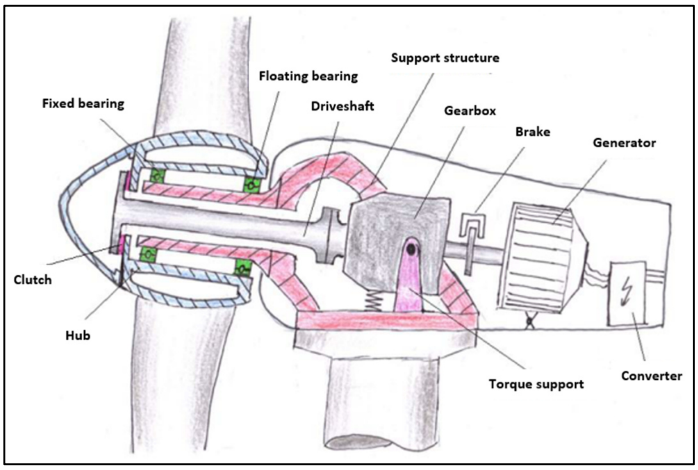

Figure 11: Drive train concept 5 (Bearings on kingpin), (based on [41])

On closer inspection, it becomes clear that teetering is possible, on condition that the "inner hub" and the "outer hub" are structurally separated from each other. This allows both, the retaining of the bearings on the kingpin and the teetering of the "outer hub" around the "inner hub". To understand how it works, the Figure 12 shows the concept 5 with a teetering hub.

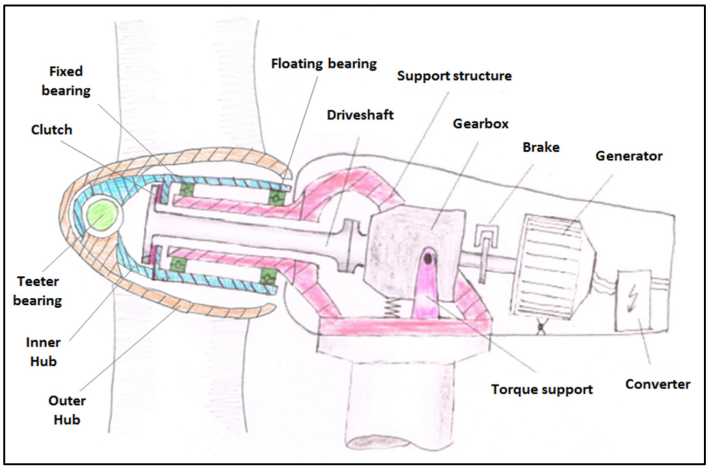

Figure 12: Teeter option of concept 5, (based on [41])

A disadvantage of this transformation is the enormous constructional effort. Another negative aspect is, the limited installation space of the teeter bearing. As explained before, the teeter bearing is ideally located in the center of gravity of the rotor-hub assembly. It follows that for turbines, build on concept 5, the feasibility in reality is to be investigated critically. In this context, the differences between downwind-turbines (less important for this thesis) and upwind-turbines (as they are considered in this thesis) are also to be worked out. As described before, differences can exist for example due to the tilt angle of the rotor, the cone angle and the prebend of the blades.

When looking at the concepts with direct drive, the installation of a teetering hub would be possible for the concepts 6 and 7. There are only minor structural changes, when comparing with the corresponding gearbox concepts (concepts 1 and 4). The structures are shown in the appendix (Figures A-19 to A-22). For the concept 8 it is different. Figure 13 shows the concept 8. Similar to the concept 5 it is difficult to teeter, because of both the bearings on the kingpin integrated into the hub and the rotor of the direct drive integrated in the hub.

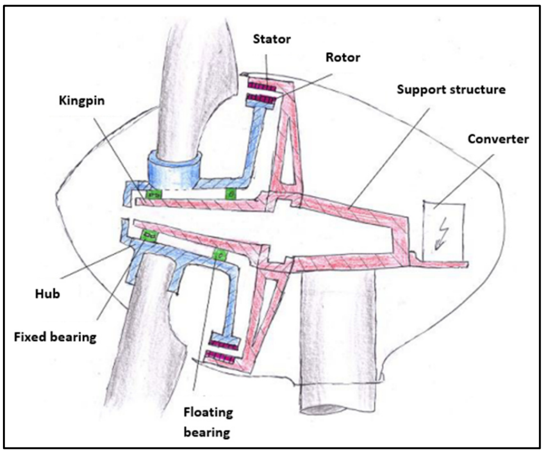

Figure 13: Drive train concept 8 (Bearings on kingpin with direct drive), (based on [41])

But a teetering hub for this concept would also be feasible theoretically. For this, it is necessary to change the structural design, like described for concept 5 before. Such a transformation is disadvantageous, too, as a result of an enormous constructional effort and again the feasibility in reality have to be checked for the same reasons described before.

At this point, the relevance of the drive train concepts is highlighted for the comparison of the UpWind 20 MW Wind Turbine and an upscaled turbine (if applicable turbines) in Chapter 6. If the concept does not provide the possibility of teetering, the design of an equivalent two-bladed wind turbine (like it is planned within an upcoming research project) will be enormously complex, because a complete overhaul of at least the drive train concept is necessary. This aspect is not to be neglected, when weighting the evaluation criteria.

4.2.1.3 Availability of further information

Further criteria are resulted from the presence of further information of the turbines. With regard to the upcoming upscaling (Chapter 5), it may be necessary to include further data, which is not listed in the Tables 06 to 10. The further data can be different in nature. A total of four criteria were defined:

- Availability of turbine model (e.g. aeroelastic model, CAD model, etc.)
- Availability of simulation data (e.g. load simulation, CFD simulations, etc.)
- Availability of controller information (e.g. torque and load data, program, etc.)
- Availability of further literature (e.g. data sheets, publications, projects, etc.)

Because all evaluation criteria, which are described before, are not to be weighted as equivalent, an allocation of weighting factors is made in the next chapter.

4.2.2 Weighting factors

In principle, it is possible to weight the evaluation criteria with different weighting-factors. This is made in order to be able to carry out a result-oriented evaluation. The evaluation criteria are weighted with decimal values between 0 and 1, which can be overall summed to 1, respectively 100 %. The weighting-factors were given by the major assessment of the criteria against each other. This means that the importance of the criteria for the further course of the work was weighted. This process was carried out on a form, which is so-called “Dominance-array” (German: Dominanzmatrix). The form is shown in the appendix (Table A-03). The Table 12 summarizes the evaluation criteria and shows the corresponding weighting-factors.

Evaluation criterion	Weighting-factor
Completeness “Operational data”	0.09
Completeness “Rotor”	0.13
Completeness “Blades”	0.13
Completeness “Hub, Nacelle, Tower”	0.09
Completeness “Drive train”	0.04
Possibility of teetering hub	0.21
Availability of turbine model	0.09
Availability of simulation data	0.07
Availability of controller information	0.02
Availability of further literature	0.13
Sum	**1.00**

Table 12: Weighting-factors (Evaluation of turbines for upscaling)

After the weighting-factors are clear, the following chapter shows the evaluation process according to VDI 2225.

4.2.3 Evaluation process

As previously mentioned the different turbines are evaluated by using points. The evaluation scale ranges from 0 to 4 points [42]. The corresponding meanings are shown in Table 13.

Points	Meaning	Assessment
0	Unsatisfactory	Far below average
1	Just tolerable	Below average
2	Adequate	Average
3	Good	Above average
4	Very good (ideal)	Far above average

Table 13: Evaluation scale by VDI 2225, (based on [42])

In order to determine the overall quality of the turbines, the points per turbine are first summed, and then the so-called “Technical Value W_t” (German: “Technische Wertigkeit W_t”) is calculated. It is calculated from the ratio of the reached score of a turbine to the maximum score [42]:

$$W_t = \frac{\Sigma_{Reached\ Points}}{\Sigma_{Maximum\ Points}} \tag{4.1}$$

According to VDI 2225, a defined scale of Technical Values W_t is available for the evaluation of varieties. In this context the varieties are given by the different turbines. This scale is shown in Table 14.

Evaluation	Maximum Technical Value
Very good turbine	$W_t > 0.8$ (80 %)
Good turbine	$W_t = 0.7$ (70 %)
Unsatisfactory turbine	$W_t < 0.6$ (60 %)

Table 14: Maximum Technical Values by VDI 2225, (based on [42])

The result of the evaluation will be a ranking of the different turbines. In the following the form is shown, which was used for the evaluation of the turbines. The corresponding evaluation criteria and weighting factors were entered. The results are highlighted.

Evaluation of turbines for upscaling

Problem: sheet-no.: 1 / 1

Choice of turbine(s) for upscaling

Turbines Evaluation criteria	Factor	DTU 10 MW Reference Turbine		AMSC wt10000dd SeaTitan^{TM}		MHI Vestas Offshore V164-9.0MW		Siemens Wind Turbine SWT-8.0-154		Adwen AD 8-180	
	∑ = 1	Points	Weighted Points	Points	Weighted Points	Points	Weighted Points	Points	Weighted Points	Points	Weighted Points
Completeness “Operational data”	**0.09**	4	0.36	3	0.27	4	0.36	4	0.36	4	0.36
Completeness “Rotor”	**0.13**	4	0.52	3	0.39	3	0.39	4	0.52	3	0.39
Completeness “Blade”	**0.13**	4	0.52	0	0.00	0	0.00	2	0.26	0	0.00
Completeness “Hub, Nacelle, Tower”	**0.09**	4	0.36	1	0.09	3	0.27	4	0.36	3	0.27
Completeness “Drive train”	**0.04**	4	0.16	4	0.16	4	0.16	4	0.16	4	0.16
Possibility of teetering hub	**0.21**	3	0.63	3	0.63	3	0.63	3	0.63	2	0.42
Availability of turbine model	**0.09**	3	0.27	1	0.09	1	0.09	1	0.09	1	0.09
Availability of simulation data	**0.07**	3	0.21	1	0.07	1	0.07	1	0.07	1	0.07
Availability of controller information	**0.02**	3	0.06	0	0.00	0	0.00	0	0.00	0	0.00
Availability of further literature	**0.13**	4	0.52	1	0.13	2	0.26	3	0.39	3	0.39
Sum of points	**1.00**	**36**	**3.61**	**17**	**1.83**	**21**	**2.23**	**26**	**2.84**	**21**	**2.15**
Maximum points	-	40	4.00	40	4.00	40	4.00	40	4.00	40	4.00
Technical Value W_t [%] **(= ratio to maximum points)**	**-**	**90.0**	**90.2**	**42.5**	**45.7**	**52.5**	**55.7**	**65.0**	**71.0**	**52.5**	**53.7**
Rank	**-**	**1**	**1**	**5**	**5**	**3 / 4**	**3**	**2**	**2**	**3 / 4**	**4**

Comments with indication of the turbine name:

DTU 10 MW Reference Turbine	The turbine clearly exceeds the Technical Value W_t of the other turbines. The turbine is suitable for upscaling.
Siemens Wind Turbine SWT-8.0-154	The turbine reached the minimum Technical Value W_t of 60 %. The turbine is suitable for upscaling.

Decision **The DTU 10 MW Reference turbine is to be upscaled!**

Evaluation scale:	0 – unsatisfactory, 1 – just tolerable, 2 – adequate, 3 – good, 4 – very good
Weighting-factors:	Decimal values between 0 and 1, which are overall summed to 1
Acceptable turbine:	Technical Value $W_t \geq 60$ %, otherwise check turbine and/or evaluation!

Table 15: Form sheet - Evaluation of turbines for upscaling

Some aspects and decisions of the evaluation are to be looked at closer:

First of all, when looking at the five different criteria of completeness, the percentage of the existing data within the respective data classes (see Tables 06 to 10) was determined, in order to assign the points. Because the evaluation scale ranges from 0 to 4 points, 20 percent increments were chosen to evaluate the completeness (for example 100 % to 81 % = 4 points, 80 % to 61 % = 3 points, and so on). As a result, the points shown on the form could be concluded.

For the criterion „possibility of teetering hub“ the drive trains of the turbines were analyzed in detail, concerning the eight concepts described above. Whether and under which restrictions the respective concepts can teeter is also described in detail in Chapter 4.2.1.2. Taking all available information into account, the turbines were assigned to the different concepts:

- DTU 10 MW Reference Turbine: Concept 1 or 2 (reasoned assumption)
- AMSC wt10000dd SeaTitan^{TM}: Concept 7 (reasoned assumption)
- MHI Vestas Offshore V164-9.0 MW: Concept 4 (reasoned assumption)
- Siemens Wind Turbine SWT-8.0-154: Concept 7 (reasoned assumption)
- Adwen AD 8-180: Concept 5 (reasoned assumption)

Overall, the evaluation was difficult due to the little information, so a conservative strategy was chosen. For all turbine, except the Adwen AD 8-180, teetering is possible without restrictions theoretically.

As already mentioned, further information of the turbines is considered for the four different criteria of availability. Both, the technical specifications shown within the appendix, as well as the complete reports and data sheets (see [8], [17], [22], [24], [25], [26], [28], [29], [30], [32], [33], [34] and [35]) were taken into account. The same is true for further information resulting from the literature research, for example tables of structural data and load simulation results. On this basis, the respective points of the evaluation, which are shown on the form, were assigned.

4.3 Decision: Turbine for upscaling

The evaluation on the form produced the following result: In the further course of this work, the DTU 10 MW Reference Turbine will be upscaled. As a consequence, it will be possible to compare the UpWind 20 MW Wind Turbine with a further research turbine in this work. All other theoretically suitable turbines will not be scaled up. This has many reasons. On the one hand, the Technical Values W_t are significantly lower and three of them are not acceptable. On the other hand, the low availability of model, load and controller data of the turbines could be a problem in the further course of this work (upscaling process and concept design). As already mentioned, the concept design will take place after the upscaling. The DTU 10 MW Reference Turbine does not have these negative aspects. With a Technical Value W_t that is considered as "very good", the turbine is ideal for upscaling.

Chapter 5

Upscaling of turbines

After the decision to upscale the DTU 10 MW Reference Turbine, this chapter starts with the upscaling process. The process finishes with a tabular summary, which compares the configurations and the parameters of the starting turbine and the upscaled turbine. Following this, some aspects (e.g. the applicability of knowledge from current scientific literature) are looked at closer. This part of the thesis (Chapter 5.2) is named “concept design”. The chapter finishes with a profound discussion of the upscaling results as well as the results from concept design.

5.1 Upscaling process

As Table 03 shows, and as already explained, the rotor radius R represents the reference parameter of the upscaling process. Thus, the first step is to determine the upscaled rotor radius R_2. The input rotor diameter D_1 (see Table 06) is known as well as the input rotor radius R_1. It is:

$$R_1 = \frac{D_1}{2} = \frac{178{,}3\ m}{2} = 89.15\ m \tag{5.1}$$

It is also known that the turbine is to be upscaled from a maximum rated power output $P_1 = 10$ MW to $P_2 = 20$ MW. According to the relations of Table 03, it is:

$$\frac{P_1}{P_2} = \left(\frac{R_1}{R_2}\right)^2 \tag{5.2 a}$$

$$R_2 = \frac{R_1}{\sqrt{P_1/P_2}} = \frac{89{,}15\,m}{\sqrt{10\,MW/20\,MW}} = 126.08\,m \tag{5.2 b}$$

Thus, the upscaled rotor diameter is:

$$D_2 = 2 \cdot R_2 = 2 \cdot 126.08\,m = 252.16\,m \tag{5.3}$$

This results in the following swept area:

$$A_2 = \pi \cdot \frac{D^2}{4} = \pi \cdot \frac{(252.16\,m)^2}{4} = 49{,}950\,m^2 \tag{5.4}$$

The corresponding relation coefficient is:

$$\frac{R_1}{R_2} = \frac{89.15\,m}{126.08\,m} = \frac{\sqrt{2}}{2} = 0{,}7071 \tag{5.5}$$

This coefficient is important for all further parameters to be upscaled. This means, that the coefficient can be used for all other relations shown in Table 03, as well as all further lengths and parameters. As mentioned in Chapter 2.4 the geometric similarity is maintained as far as possible, for example by using a standardized factor q. Because of this it would be useful to use the relation coefficient also as the standardized factor q. As a consequence, the corresponding scale dependence of all other length and parameters will be ~ R^1. It is:

$$\frac{R_1}{R_2} = 0{,}7071 = q \tag{5.6}$$

Taking the relation coefficient, respectively the standardized factor q, into account, the upscaling of the other parameters will be performed in the following.

For that to happen, both the data of the DTU 10 MW Reference Turbine from Table 06 as well as the data from Table A-02 (shown in the appendix) is used.

5.1.1 General properties

While maintaining the upscaling laws of Chapter 2.4, a lot of parameters are still the same, when performing upscaling, for example the wind regime, the rotor orientation and the power regulation. Both, the starting and the upscaled turbine are created for an operation at "IEC class IA" conditions. The rotor orientation is "upwind" at "variable speed" and the power regulation is via a "pitch control". The number of blades remains the same, too:

$$N_2 = N_1 = 3 \tag{5.7}$$

Also the operational wind speeds of the incoming flow are the same:

$$v_{2\,cut-in} = v_{1\,cut-in} = 4\,m/s \tag{5.8}$$

$$v_{2\,rated} = v_{1\,rated} = 11.4\,m/s \tag{5.9}$$

$$v_{2\,cut-out} = v_{1\,cut-out} = 25\,m/s \tag{5.10}$$

To maintain the tip speed and the whole tip speed ratio, the rotational speed can be scaled up. The relation for rotational speed was shown in Table 03. For the maximum rotor speed the following can be calculated:

$$\frac{\Omega_{1\,MAX}}{\Omega_{2\,MAX}} = \left(\frac{R_1}{R_2}\right)^{-1} \tag{5.11 a}$$

$$\Omega_{2\,MAX} = \frac{\Omega_{1\,MAX}}{(R_1/R_2)^{-1}} = \frac{9.6\,rpm}{0.7071^{-1}} = 6.78\,rpm \tag{5.11 b}$$

So the maximum tip speed maintains:

$$v_{2\,MAX\,Tip} = \frac{2\cdot\pi\cdot R_2\cdot\Omega_{2\,MAX}}{60} = v_{1\,MAX\,Tip} = \frac{2\cdot\pi\cdot R_1\cdot\Omega_{1\,MAX}}{60} \tag{5.12 a}$$

$$v_{2\,MAX\,Tip} = \frac{2\pi\cdot 126.08\,m\cdot 6.78\,rpm}{60} = v_{1\,MAX\,Tip} = \frac{2\pi\cdot 89.15\,m\cdot 9.6\,rpm}{60} = 90\,m/s \tag{5.12 b}$$

The relation of Equation 5.11 can be applied also for the minimum rotor speed. It is:

$$\Omega_{2\,MIN} = \frac{\Omega_{1\,MIN}}{(R_1/R_2)^{-1}} = \frac{6.0\,rpm}{0.7071^{-1}} = 4.24\,rpm \tag{5.13}$$

The speed of the fast rotating shaft of the generator will be the same for the starting turbine as well as for the upscaled turbine. In order to achieve this, the gearbox ratio changes. Because there is no defined relation for the gearbox ratio, the adaptation is made according to the factor q. It is:

$$\frac{\mathrm{i}_1}{\mathrm{i}_2} = \left(\frac{R_1}{R_2}\right)^1 = q \tag{5.14 a}$$

$$\mathrm{i}_2 = \frac{\mathrm{i}_1}{q} = \frac{50.0}{0.7071} = 70.7 \tag{5.14 b}$$

Thus, the speed of the fast rotating shaft of the generator is:

$$\Omega_{Generator} = \Omega_{1\,MAX} \cdot i_1 = \Omega_{2\,MAX} \cdot i_2 \tag{5.15 a}$$

$$\Omega_{Generator} = 9.6\,rpm \cdot 50 = 6.78\,rpm \cdot 70.7 = 480\,rpm \tag{5.15 b}$$

The used generator type itself does not change in terms of upscaling. The same is true for the used gearbox type. Both turbines are equipped with a “permanent magnet synchronous generator (PMG)” and a “multi-stage gearbox”. Whether such a combination is useful for the upscaled turbine cannot be answered at this point. In respect to this, profound considerations are necessary, which cannot be made within this thesis, because of the high complexity. For example, due to the increased rated power output and at the same time the constant generator speed, the rated moment of the generator also increases. The higher the rated moment of the generator, the higher the number of pole pairs and as a consequence the bigger and heavier the generators [43]. Following this, a potential for optimization of the drive train is to be identified. The best combination of power output, weight and size can be found, taking a lot of other parameters (e.g. eigenfrequencies of the tower, forces and moments on the support structure, etc.) into account.

5.1.2 Geometric properties

To upscale lengths, the constant factor q is used, too, as described above. Thus, the blade span is:

$$\frac{\mathrm{L}_{1\,Span}}{\mathrm{L}_{2\,Span}} = \left(\frac{R_1}{R_2}\right)^1 = q \tag{5.16 a}$$

$$\mathrm{L}_{2\,Span} = \frac{\mathrm{L}_{1\,Span}}{q} = \frac{86.35\,m}{0.7071} = 122.12\,m \tag{5.16 b}$$

The blade prebend $\mathrm{L}_{\mathrm{Prebend}}$ as well as the blade chord lengths c of every profile cannot be upscaled, because the aerodynamic profiles are not known yet. The aerodynamic properties are of crucial importance for the starting turbine as well as for the upscaled turbine. The properties are depending among others on the blade profile and the blade prebend. For this reason, a simple upscaling according to the constant factor q would be possible theoretically, but not sensible in reality. To determine the optimal profile and the blade prebend, elaborate simulations (e.g. CFD simulations) are necessary. The same is true for determining the optimal blade material.

According to the principle of Equation 5.16, the hub height and the hub diameter can be upscaled:

$$\mathrm{H}_{2\,Hub} = \frac{\mathrm{H}_{1\,Hub}}{q} = \frac{119.0\ m}{0.7071} = 168.3\,m \tag{5.17}$$

$$\mathrm{D}_{2\,Hub} = \frac{\mathrm{D}_{1\,Hub}}{q} = \frac{5.6\ m}{0.7071} = 7.9\,m \tag{5.18}$$

The tower height and the diameters of the tower sections at the foundation (0 m) and at the nacelle can be upscaled, too:

$$\mathrm{H}_{2\,Tower} = \frac{\mathrm{H}_{1\,Tower}}{q} = \frac{115.63\ m}{0.7071} = 163.52\,m \tag{5.19}$$

$$\mathrm{D}_{2\,Tower\,high} = \frac{\mathrm{D}_{1\,Tower\,high}}{q} = \frac{5.5\ m}{0.7071} = 7.77\,m \tag{5.20}$$

$$D_{2\,Tower\ low} = \frac{D_{1\,Tower\ low}}{q} = \frac{8.3\ m}{0.7071} = 11.73\ m \tag{5.21}$$

The hub height and the tower height are site specific parameters. This means that in reality an adjustment is possible to improve for example the dynamic of the turbine on its offshore location. For this reason, the diameters of the tower segments are only theoretical values. For the dimensions of the nacelle itself, it is:

$$L_{2\,Nacelle\ x} = \frac{L_{1\,Nacelle\ x}}{q} = \frac{10.0\ m}{0.7071} = 14.14\ m \tag{5.22}$$

$$L_{2\,Nacelle\ y} = \frac{L_{1\,Nacelle\ y}}{q} = \frac{10.0\ m}{0.7071} = 14.14\ m \tag{5.23}$$

$$L_{2\,Nacelle\ z} = \frac{L_{1\,Nacelle\ z}}{q} = \frac{15.0\ m}{0.7071} = 21.21\ m \tag{5.24}$$

The tilt angle of the nacelle and the cone angle of the blades are the same for both turbines. This is because the similarity is maintained as far as possible (see upscaling law number 3, Chapter 2.4.1). It is:

$$\alpha_2 = \alpha_1 = 5.0° \tag{5.25}$$

$$\beta_2 = \beta_1 = -2.5° \tag{5.26}$$

The last step is to scale up the structural properties of the turbine.

5.1.3 Structural properties

In view of the square-cube law described in Chapter 2.4.2.1, at this point the weights of the turbine parts are initially calculated by assuming the scale dependence of ~ R^3. Accordingly, these weights are the most negative ones. In the further course of this thesis it is probably possible to show some potentials for weight reduction, for example within the concept design of the upscaled turbine in the following chapter, due to the use of some scaling trends from current scientific literature. At this point, for the rotor weight the following equation can be applied:

$$\frac{W_{1\,Rotor}}{W_{2\,Rotor}} = \left(\frac{R_1}{R_2}\right)^3 \tag{5.27 a}$$

$$W_{2\,Rotor} = \frac{W_{1\,Rotor}}{(R_1/R_2)^3} = \frac{230.6\ t}{0.7071^3} = 652.2\ t \tag{5.27 b}$$

The same relation is true for the weight of a blade, the hub and the nacelle:

$$W_{2\,Blade} = \frac{W_{1\,Blade}}{(R_1/R_2)^3} = \frac{41.7\ t}{0.7071^3} = 117.9\ t \tag{5.28}$$

$$W_{2\,Hub} = \frac{W_{1\,Hub}}{(R_1/R_2)^3} = \frac{105.5\ t}{0.7071^3} = 298.4\ t \tag{5.29}$$

$$W_{2\,Nacelle} = \frac{W_{1\,Nacelle}}{(R_1/R_2)^3} = \frac{446.0\ t}{0.7071^3} = 1{,}261.5\ t \tag{5.30}$$

When considering the blade, the weight can only be theoretically upscaled, because the aerodynamic profile and the blade material are unknown (see Chapter 5.1.2). The nacelle weight depends, as already mentioned, on its components. So the calculated weight is a site specific parameter. In addition, the weight of the tower can only be theoretically upscaled. This is due to the fact, that the weight of the tower depending on its high and on the corresponding eigenfrequencies (natural frequencies), caused on oscillation by the incoming flow. At this point the natural frequencies of the tower are not known. Because of that the tower weight can be theoretically calculated taking the already calculated height (Equation 5.19) into account. It is:

$$W_{2\,Tower} = \frac{W_{1\,Tower}}{(R_1/R_2)^3} = \frac{628.4\ t}{0.7071^3} = 1{,}777.4\ t \tag{5.31}$$

For the inertia of the turbine parts another relation of Table 03 can be applied. The hub inertia is:

$$\frac{I_{1\,Hub}}{I_{2\,Hub}} = \left(\frac{R_1}{R_2}\right)^5 \tag{5.32 a}$$

$$I_{2\,Hub} = \frac{I_{1\,Hub}}{(R_1/R_2)^5} = \frac{325{,}670\ kg \cdot m^2}{0.7071^5} = 1{,}842{,}356\ kg \cdot m^2 \tag{5.32 b}$$

The nacelle inertia about yaw-axis can be scaled up according to the same relation:

$$I_{2\,Nacelle\,Yaw} = \frac{I_{1\,Nacelle\,Yaw}}{(R_1/R_2)^5} = \frac{7{,}326{,}346\ kg \cdot m^2}{0.7071^5} = 41{,}446{,}058\ kg \cdot m^2 \tag{5.33}$$

These inertias are only theoretical values, like the weight of the blades, of the nacelle and of the tower. For the implementation of the turbine in reality, the values have to be checked by calculations and simulations.

5.1.4 Summary

The following table summarizes the parameters, which have been upscaled before. Both, the parameters of the starting turbine (DTU 10 MW Reference Turbine) and the so-called "Upscaled DTU 20 MW Turbine" are shown.

Class	Parameter	Symbol	DTU 10 MW Reference Turbine	Upscaled DTU 20 MW Turbine
Operational data	Nominal power output	P	10 MW	20 MW
	Wind regime	IEC class	IEC class IA	Same
	Cut-in wind speed	$v_{cut\text{-}in}$	4 m/s	Same
	Nominal power output at	v_{rated}	11.4 m/s	Same
	Cut-out wind speed	$v_{cut\text{-}out}$	25 m/s	Same
Rotor	Number of blades	N	3	Same
	Rotor orientation	-	Upwind	Same
	Rotor diameter	D	178.3 m	252.16 m
	Swept area	A_{Rotor}	24,950 m²	49,950 m²
	Power regulation	-	Var. speed, pitch control	Same
	Rotor tilt angle	α	5 deg	Same
	Maximum rotor speed	Ω_{MAX}	9.6 rpm	6.78 rpm
	Minimum rotor speed	Ω_{MIN}	6.0 rpm	4.24 rpm
	Maximum tip speed	v_{Tip}	90 m/s	Same
	Rotor mass (hub + blades)	W_{Rotor}	230.6 t	652.2 t
Blade	Blade span	L_{Span}	86.35 m	122.12 m
	Blade cone angle	β	- 2.5 deg	Same
	Blade prebend	$L_{Prebend}$	3.332 m	Not yet known ①
	Aerodynamic profile	-	FFA-W3-XXX, Cylinder	Not yet known ①
	Blade material	-	GRP	Not yet known ①
	Blade mass	W_{Blade}	41.7 t	117.9 t ②

Table 16: Summary of upscaling parameters, part 1/2

Class	Parameter	Symbol	DTU 10 MW reference turbine	Upscaled DTU 20 MW turbine
Hub	Hub diameter	D_{Hub}	5.6 m	7.9 m
	Hub height	H_{Hub}	119 m	168.3 m ③
	Hub mass	W_{Hub}	105.5 t	298.4 t
	Hub inertia (shaft-axis)	I_{Hub}	325,670 kgm^2	1,842,356 kgm^2 ②
Nacelle	Nacelle length (x-axis)	$L_{Nacelle\ x}$	10 m	14.14 m
	Nacelle width (y-axis)	$L_{Nacelle\ y}$	10 m	14.14 m
	Nacelle height (z-axis)	$L_{Nacelle\ z}$	15 m	21.21 m
	Nacelle mass	$W_{Nacelle}$	446.0 t	1,261.5 t ③
	Nacelle inertia (Yaw-axis)	$I_{Nacelle\ Yaw}$	7,326,346 kgm^2	41,446,058 kgm^2 ②
Tower	Tower height	H_{Tower}	115.63 m	163.52 m ③
	Tower outer diam. (highest section)	$D_{Tower\ high}$	5.5 m	7.77 m ②
	Tower outer diam. (lowest section)	$D_{Tower\ low}$	8.3 m	11.73 m ②
	Tower mass	W_{Tower}	628.4 t	1,777.4 t ②
Drive train	Gearbox type	-	Multiple-stage gearbox	Same
	Gearbox ratio	i	50	70.7
	Generator type	-	PMG	Same
	Generator speed	$\Omega_{Generator}$	480 rpm	Same

① Not upscalable, because overwork or redesign required. Elaborate simulations (e.g. CFD simulations) are necessary.
② Theoretical value depending on upscaling. This value can be different in reality, because of necessary design optimization.
③ Site specific parameters. This value can be different in reality. In this context only theoretical value.

Table 16: Summary of upscaling parameters, part 2/2

5.2 Concept design

Within the concept design some aspects are to be investigated, which finish and improve the design of the upscaled turbine. At first, the conclusions from the current scientific knowledge (Chapter 2.4.3) are applied to the parameters of the upscaled turbine. As a result, some weight reductions can be calculated. Another aspect of the concept design is given by the appearance of the whole upscaled turbine. Therefore, the corresponding CAD model is looked at closer.

5.2.1 Use of knowledge from current scientific literature

With consideration of current scientific knowledge (Chapter 2.4.3) an overwork of the expected weights is possible. In respect to this, it is necessary to apply the different scale dependences as they are described and summarized within Table 04 above. So for the weight of the blades it is:

$$\frac{W_{1\,Blade}}{W_{2\,Blade}} = \left(\frac{R_1}{R_2}\right)^{2.3} \tag{5.34 a}$$

$$W_{2\,Blade} = \frac{W_{1\,Blade}}{(R_1/R_2)^{2.3}} = \frac{41.7\ t}{0.7071^{2.3}} = 92.5\ t \tag{5.34 b}$$

When comparing this to the cubic calculation of the blade weight (Equation 5.28) a weight reduction can be calculated. It is:

$$\Delta W_{Blade} = 117.9\ t - 92.5\ t = 25.4\ t \tag{5.35}$$

This is a reduction for more than 21 % due to the value calculated with regard to the square-cube law.

For the weight of the tower, another scale dependence according to Table 04 can be applied. It is:

$$\frac{W_{1\,Tower}}{W_{2\,Tower}} = \left(\frac{R_1}{R_2}\right)^{2.6} \tag{5.36 a}$$

$$W_{2\,Tower} = \frac{W_{1\,Tower}}{(R_1/R_2)^{2.6}} = \frac{628.4\ t}{0.7071^{2.6}} = 1{,}547.3\ t \tag{5.36 b}$$

Thus, the corresponding weight reduction according to Equation 5.31 is approximately 13 %. It is:

$$\Delta W_{Tower} = 1{,}777.4\ t - 1{,}547.3\ t = 230.1\ t \tag{5.37}$$

The weight of the nacelle remains to the square-cube law (when considering all turbine technologies, see Chapter 2.4.3.2). Taking this information into account, the weight of the whole rotor (and in line with this, also the weight of the hub) can be calculated by using the scale dependence for the tower top weight. The tower top weight of the DTU 10 MW turbine is given within Table 07 (W_{Top} = 446.0 t + 230.6 t = 676.6 t). So the tower top weight of the upscaled turbine can be calculated by:

$$\frac{W_{1\,Top}}{W_{2\,Top}} = \left(\frac{R_1}{R_2}\right)^{2.8} \qquad (5.38\text{ a})$$

$$W_{2\,Top} = \frac{W_{1\,Top}}{(R_1/R_2)^{2.8}} = \frac{676.6\,t}{0.7071^{2.8}} = 1{,}785.6\,t \qquad (5.38\text{ b})$$

Now, the unchanged weight of the nacelle (Equation 5.30) can be subtracted from the tower top weight. This results in the weight of the rotor:

$$W_{Rotor} = W_{Top} - W_{Nacelle} \qquad (5.39\text{ a})$$

$$W_{Rotor} = 1785.6\,t - 1{,}261.5\,t = 524.1\,t \qquad (5.39\text{ b})$$

So, the weight reduction is approximately 20 %. By subtraction of the weight of the three blades, the weight of the hub can be calculated:

$$W_{Hub} = W_{Rotor} - 3 \cdot W_{Blade} \qquad (5.40\text{ a})$$

$$W_{Hub} = 524.1\,t - 3 \cdot 92.5\,t = 246.6\,t \qquad (5.40\text{ b})$$

This is again a weight reduction. Due to the value calculated with regard to the square-cube law the reduction is more than 17 %.

Finally, the Table 17 summarizes the calculations based on current scientific literature. All weight reductions are shown, too.

Parameter	Symbol	Classical upscaling relations	Current scientifc literature	Weight reduction
Blade mass	W_{Blade}	117.9 t	92.5 t	≈ 21 %
Tower mass	W_{Tower}	1,777.4 t	1,547.3 t	≈ 13 %
Tower top mass	W_{Top}	/	1,785.6 t	/
Nacelle mass	$W_{Nacelle}$	1,261.5 t	1,261.5 t	/
Rotor mass	W_{Rotor}	652.2 t	524.1 t	≈ 20 %
Hub mass	W_{Hub}	298.4 t	246.6 t	≈ 17 %

Table 17: Summary "Classical upscaling relations vs. current scientific literature"

5.2.2 Blade design (basics)

The performance of a wind turbine essentially depends on the structural and aerodynamic properties of the rotor blades [2, 7]. As already mentioned (Chapter 2.4.1 and Chapter 5.1.2), the simple usage of the upscaling relations is not correct, because an overwork or redesign is required and detailed simulations have to be done. This chapter is intended to explain the reasons for this.

In general, a rotor blade consists of many different so-called rotor blade profiles, which are connected to each other (see Figure 14).

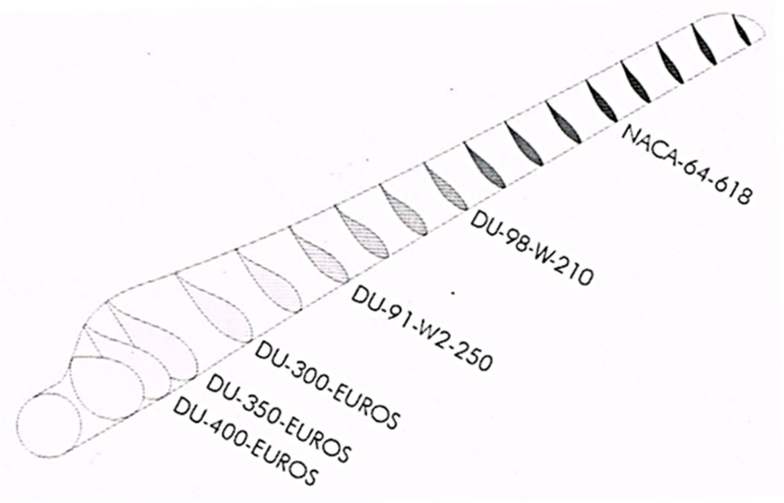

Figure 14: Blade profiles (schematic), (Source: [7])

When the rotor blades are scaled up, the rotor blade profiles as well as the distances between them increase, too. Furthermore, the weight increases, which can result in strength problems [2], because the stiffness of the blades are lower due to the increased distances between the profiles (risk of buckling, see Chapter 3.1.1).

In addition to the strength of the rotor blades, the aerodynamic properties are of crucial importance for the performance of the system. These properties depend on the so-called glide ratio E in general. It describes the ratio of lift (lift coefficient c_A) to drag (drag coefficient c_W) [2]:

$$E = \frac{c_A}{c_W} \tag{5.41}$$

The higher the glide ratio is, meaning the higher the lift coefficient and the lower the drag coefficient, the better are the aerodynamic properties. It is to be noted, that the glide ratio depends on the respective angle of attack of a rotor blade. Another parameter to describe the aerodynamic properties is the so-called Lock Number γ (also known as Mass Number). It describes the ratio of aerodynamic forces to inertial forces of mass [44].

$$\gamma = \frac{2 \cdot \rho \cdot R^4 \cdot C_{l\alpha} \cdot c}{I} \tag{5.42}$$

The Lock Number was developed for the aerodynamic properties of helicopters. In general, the aerodynamic damping depends mainly on the Lock Number. The higher the Lock Number is, the better is the aerodynamic profile [44]. In this context, either the glide ratio E or the Lock Number γ can be calculated, because some of the required parameters for calculation (e.g. lift coefficient c_A, drag coefficient c_W, slope of the lift-curve $C_{l\alpha}$, blade chord c, etc.) are unknown.

The performance of a rotor blade is also influenced by flow-mechanical parameters, for example the Reynolds number. It describes the influence of friction forces in the flow, or in detail the interactions between the blade profile and the viscosity, which characterizes the current flow conditions [2]. The retention of both the glide ratio E (and also Lock Number γ) and the Reynolds number is not possible, due to the upscaling. In order to ensure constant (or even improved) aerodynamic properties, larger profiles and also more profiles distributed over the blade length are necessary. With these profiles, simulations and if necessary wind tunnel tests have to be done, so that the aerodynamic properties can be demonstrated.

In this work, the above-mentioned aspects cannot be considered in detail because of the high complexity and the expected high time expenditure.

5.2.3 Geometric model (CAD model)

To see the impressive dimensions of the upscaled 20 MW turbine, the CAD model of the DTU 10 MW turbine (starting turbine) has to be upscaled according to the standardized factor q. Figure 15 presents the results.

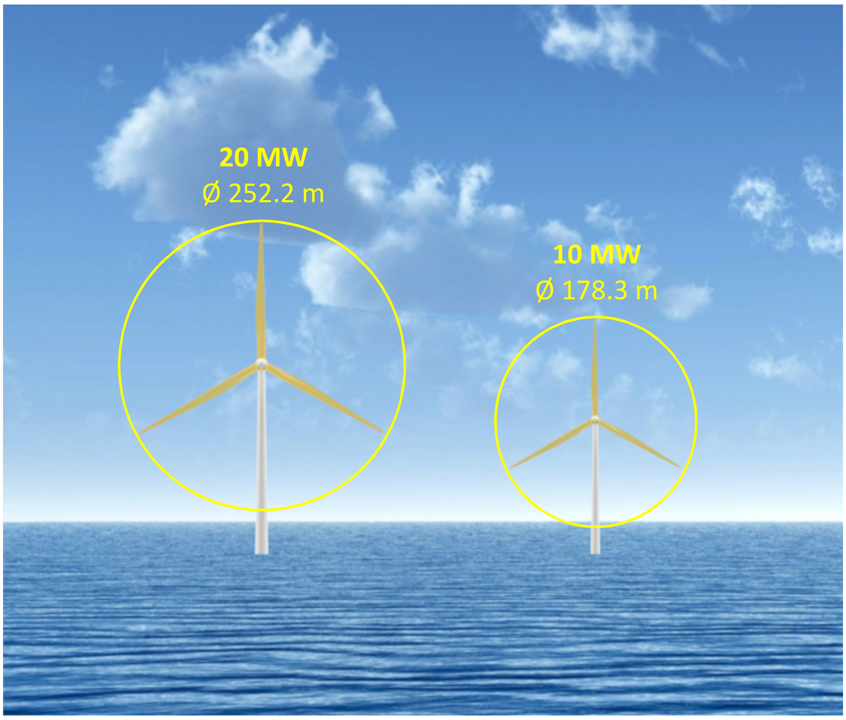

Figure 15: Photorealistic image of upscaled 20 MW turbine, (Source of background: V3 Wallpaper; available from: http://www.v3wall.com/de/html/pic_show/pic_show_5395.html)

When looking at the model it is to be noted, that not all lengths and diameters are the same as those calculated in Chapter 5.1. The differences can be attributed to the original CAD files of the DTU 10 MW turbine, the quality of which is to be assessed as negative. To highlight the dimensions, the corresponding rated power outputs and rotor diameters are added to the figure.

5.3 Discussion of the results

In summary, due to the work of the upscaling process and the concept design, profound data of a “new” 20 MW turbine could be generated. Most of the parameters are of theoretically nature, based on some basic laws and relations (see Chapter 2.4.1 and 2.4.2), respectively some basic mathematic equations, for example the square-cube law (see Chapter 2.4.2.1). When considering newest scientific knowledge of upscaling, there is the possibility given to improve the design, respectively the weight of the turbine components. As already discussed in Chapter 2.4.3.8, this fact is to be assessed as critical, because the applicability to real systems (practical implementation of the turbine) is dependent on the perception (or preoccupation) of the respective scientific studies and, ultimately, no "real" correct answer exists. However, taking these aspects into account, the results of the upscaling process as well as the concept design are very comprehensive to do an interesting comparison between two 20 MW turbine systems. The results are definitely not to be described as a "real" and operating turbine, because for that a lot of further work, for example structural and aerodynamic simulation, is missing. But nevertheless, the results of the upscaling process and concept design are ideally as a starting point for further studies.

Chapter 6

Comparison of turbines

This chapter focuses on an objective comparison between the UpWind 20 MW wind turbine and the upscaled DTU 20 MW turbine. Therefore, at first, the pros and cons of the turbines are listed and explained. After that the parameters of both turbines are compared. On the basis of both an evaluation, again in accordance to the method of VDI 2225, is to be carried out on a form sheet. For this evaluation useful evaluation criteria, based among other things on the pros and cons of the turbines, have to be defined. In addition, corresponding weighting-factors are to be assigned. After the comparison is done, the results will be discussed in detail. Finally, a recommendation for further research projects at HAW Hamburg can be made.

6.1 Comparison by pros and cons of turbines

As a first step, the pros and cons of both 20 MW turbines are compared with each other. They are first explained and after that, for the sake of clarity, the pros and cons are listed in tabulated form.

6.1.1 UpWind 20 MW Wind Turbine

As already mentioned, the UpWind 20 MW Wind Turbine represents the reference turbine for the comparison. A big advantage of this turbine is, that the turbine was optimized after upscaling from the 5 MW starting turbine. This means, that a complete overwork has been done within the UpWind project, including a detailed aerodynamic blade design as well as the design of a suitable controller. All parameters and properties are specially designed for a 20 MW system. The geometric and structural parameters are tabled within the appendix of the pre-design report (see [17]). The same is true for the blade profile. Detailed mass distribution as well as bending properties and geometric data are listed within the pre-design report. In contrast, the final report (see [8]) is formulated very superficially. It is not clear, how the respective methods (design, calculation, simulation, etc.) were used to achieve the described results. Another negative aspect is, that the controller data was not published and in respect to this, the data is not available for further research purposes. The simulation data is only available in tabulated form. Unfortunately, an aeroelastic model (from which a CAD model could be derived) for further simulations or geometric considerations does not exist, too.

Table 18 summarizes the pros and cons, which were explained previously:

UpWind 20 MW Wind Turbine	
Pros	**Cons**
▪ Design optimized turbine (upscaled turbine, which was optimized)	▪ No detailed description of methods (design, calculation, simulation, etc.)
▪ Detailed blade design (aerodynamic design) done	▪ Simulation data (load simulation, CFD simulation, etc.) only available in tabulated form (parameters)
▪ Detailed controller design done	▪ Controller data and codes are not available
▪ Availability of geometric and structural parameters	▪ No aeroelastic model (and no CAD model)

Table 18: Pros and cons "UpWind 20 MW Wind Turbine"

6.1.2 Upscaled DTU 20 MW Turbine

When looking at the upscaled DTU 20 MW Turbine, the turbine based on profound and optimized data of the DTU 10 MW Turbine. However, due to the upscaling, partly only theoretical parameters were generated. This fact is true for geometric and structural parameters as well as for simulation data. In a similar way, it is true for the blade design and the controller information. Concerning this, for the starting turbine detailed information exists. Within this thesis no further blade and controller design have been done for the upscaled 20 MW turbine, because of, as already mentioned, the high complexity. In contrast to this, a CAD model (but no aeroelastic model) exist for the upscaled 20 MW turbine. The CAD model of the 10 MW turbine was scaled to a 20 MW turbine, but without any modification on, for example the blade profile. In general, the grade of detail of both models is inadequate, which is due to the poor quality of the input file. Overall, a positive aspect is, that the upscaled turbine clarifies the dimensions of a 20 MW system, even if the data has to be verified.

Subsequently, for the DTU 20 MW Turbine, which was upscaled within this thesis, Table 19 summarizes the pros and cons:

Upscaled DTU 20 MW Turbine	
Pros	**Cons**
▪ Profound data before upscaling (10 MW turbine is optimized)	▪ Partly only theoretical parameters (parameters are not optimized)
▪ Simulation data of 10 MW turbine (load simulation, CFD simulation, etc.) are available	▪ Simulation data of 20 MW turbine (load simulation, CFD simulation, etc.) are not available
▪ Detailed blade design for 10 MW turbine (aerodynamic design) done	▪ No further blade design of 20 MW turbine (aerodynamic design) done
▪ Detailed controller information for 10 MW turbine are available	▪ No further controller information for 20 MW turbine are available
▪ CAD Model of 10 MW turbine and derived CAD model of upscaled 20 MW turbine are available	▪ No aeroelastic model and quality and level of detail of existing CAD models are inadequate

Table 19: Pros and cons "Upscaled DTU 20 MW Turbine"

6.2 Comparison by parameters of turbines

Class	Parameter	Symbol	UpWind 20 MW Wind Turbine	Upscaled DTU 20 MW Turbine
Operational data	Nominal power output	P	20 MW	20 MW
	Wind regime	IEC class	IEC class IB	IEC class IA
	Cut-in wind speed	$v_{cut\text{-}in}$	unknown ①	4 m/s
	Nominal power output at	v_{rated}	10 m/s	11.4 m/s
	Cut-out wind speed	$v_{cut\text{-}out}$	25 m/s (reasoned assumption)	25 m/s
Rotor	Number of blades	N	3	3
	Rotor orientation	-	Upwind	Upwind
	Rotor diameter	D	252 m	252.16 m
	Swept area	A_{Rotor}	49,850 m^2	49,950 m^2
	Power regulation	-	Var. speed, pitch control	Var. speed, pitch control
	Rotor tilt angle	α	5 deg	5 deg
	Maximum rotor speed	Ω_{MAX}	6.05 rpm	6.78 rpm
	Minimum rotor speed	Ω_{MIN}	2.58 rpm	4.24 rpm
	Maximum tip speed	v_{Tip}	80 m/s	90 m/s
	Rotor mass (hub + blades)	W_{Rotor}	770 t	652.2 t / 524.1 t ④
Blade	Blade span	L_{Span}	123 m	122.12 m
	Blade cone angle	β	- 2.5 deg	- 2.5 deg
	Blade prebend	$L_{Prebend}$	Existing, but unknown ①	Not yet known ②
	Aerodynamic profile	-	NACA, DU, Cylinder	Not yet known ②
	Blade material	-	GRP	Not yet known ②
	Blade mass	W_{Blade}	105.2 t (calculated)	117.9 t ③ / 92.5 t ④
Hub	Hub diameter	D_{Hub}	unknown ①	7.9 m
	Hub height	H_{Hub}	153 m	168.3 m ⑤
	Hub mass	W_{Hub}	454.2 t	298.4 t / 246.6 t ④
	Hub inertia (shaft-axis)	I_{Hub}	3,709,632 kgm^2	1,842,356 kgm^2 ③
Nacelle	Nacelle length (x-axis)	$L_{Nacelle\ x}$	unknown ①	14.14 m
	Nacelle width (y-axis)	$L_{Nacelle\ y}$	unknown ①	14.14 m
	Nacelle height (z-axis)	$L_{Nacelle\ z}$	unknown ①	21.21 m
	Nacelle mass	$W_{Nacelle}$	1,920 t	1,261.5 t ⑤
	Nacelle inertia (Yaw-axis)	$I_{Nacelle\ Yaw}$	83,452,480 kgm^2	41,446,058 kgm^2 ③
Tower	Tower height	H_{Tower}	unknown ①	163.52 m ⑤
	Tower outer diam. (highest section)	$D_{Tower\ high}$	8.16 m	7.77 m ③
	Tower outer diam. (lowest section)	$D_{Tower\ low}$	12.0 m	11.73 m ③
	Tower mass	W_{Tower}	2,780 t	1,777.4 t ③ / 1,547.3 t ④
Drive train	Gearbox type	-	Existing, but unknown ①	Multiple-stage gearbox
	Gearbox ratio	i	194	70.7
	Generator type	-	PMG with transv. flux	PMG
	Generator speed	$\Omega_{Generator}$	1,173.7 rpm (calculated)	480 rpm

① Unknown, because no further information could be found within the UpWind project report.
② Not upscalable, because overwork or redesign required. Elaborate simulations (e.g. CFD simulations) are necessary.
③ Theoretical value depending on upscaling. This value can be different in reality, because of necessary design optimization.
④ Value results on current scientific literature. This value can be different in reality. In this context only theoretical value.
⑤ Site specific parameters. This value can be different in reality. In this context only theoretical value.

Table 20: Comparison by parameters

On a basic view, the parameters of both turbines are relatively similar to each other. This is especially true for the geometric parameters, for example the rotor diameter D, the blade span L_{Span} as well as the outer tower diameters $D_{\text{Tower high}}$ and $D_{\text{Tower low}}$. However, this is not surprising, because both turbines are based on the same reference turbine.

What is interesting is that all listed weights of the upscaled DTU 20 MW turbine are significant lower, when comparing to the UpWind 20 MW turbine. The weights are again lower, when looking at the scaling trends from current scientific literature. An exception is the calculated blade weight W_{Blade}, which is lower for the UpWind 20 MW turbine. In this context it means, that some potentials for weight reduction could exist. These potentials could be worked out, due to a design optimization of the upscaled DTU 20 MW turbine. In the course of this, the corresponding inertias, for example the hub inertia I_{Hub} or the nacelle inertia $I_{\text{Nacelle yaw}}$ could be checked. But this is not part of this thesis.

Another interesting aspect is on the rotor speed, meaning the maximum and minimum rotor speed (Ω_{MAX} and Ω_{MIN}) as well as the maximum tip speed v_{Tip} of the whole system. When comparing both turbines in respect to this, little differences can be found. Big differences are existing for the drive train components. The turbines are equipped with different gearboxes and generators, which are operating at different generator speeds. So for practical implementation or further studies it has to be checked, which option would be the best.

Finally, it cannot be clearly stated, which of the two turbines is more suitable for further research purposes. For this reason, an objective evaluation is made in the following chapter.

6.3 Comparison by evaluation of turbines

As mentioned before an objective comparison is to be done by the evaluation of both 20 MW turbines. This comparison is to be carried out on a form sheet according to the method of VDI 2225. This method was explained in detail in

Chapter 4.2.3, so at this point no further explanations are made. In the following the comparison criteria as well as the corresponding weighting-factors are defined.

6.3.1 Comparison / Evaluation criteria

With regard to the pros and cons as well as the parameters of both turbines the following criteria were defined:

4.3.1.1 Level of detail

When looking at the criteria, which deal with the quality of the data, three criteria can be listed. These are:

- Level of detail of description of methods
- Level of detail and reliability of data source
- Information content of geometric and structural parameters

First of all, to understand or to follow up, how the parameters and data were generated, the level of detail of description of methods is to be evaluated. Where is the data from and on which basis (method) was it generated? How good is the documentation in this regard? This criterion is in close connection to the reliability of data source. Only if the data is reliable, it should be used for further considerations to exclude possible problems, which could be emerged for example due to simulation work, etc. Another aspect is the availability of the geometric and structural parameters. Is the data complete or missing some parameters? In respect to this, not only the quantity and amount of the data but rather the quality is important (so-called information content).

4.3.1.2 Availability and usability of information

Further criteria are resulted from the availability and usability of data and information of the turbines. When looking into the future maybe more profound considerations of one or even both turbines are necessary (upcoming research projects at HAW Hamburg). Such a realization would be easier the more data would be available. In this context the focus is on data from and for simulations and calculations (CFD simulation, load simulation, blade design, etc.). Also important is the availability of further literature. In summary, the following criteria were defined:

- Availability of simulation data
- Availability of aeroelastic model
- Availability of CAD model
- Availability and usability of blade design information
- Availability and usability of controller information
- Availability of further literature

4.3.1.3 Further information

Last but not least there is another criterion. It is defined by the possibility to contact scientific specialists and experts. During the work, respectively during deeper considerations, unexpected problems could be arisen, for the solution of which it may be useful to consult experts. These experts should already have dealt on the topic extensively. To contact the experts some contact information is needed. Regarding this, the availability of email addresses and telephone numbers will be the decisive factor for the evaluation.

6.3.2 Weighting factors

Similar to Chapter 4, the comparison / evaluation criteria are not to be weighted as equivalent in this case. For this reason, the so-called dominance array was again used to delineate the criteria against each other and to find the corresponding weighting-factors. The Table 21 summarizes the evaluation criteria and shows the weighting-factors. The complete dominance array can be found in the appendix (see Table A-04).

Evaluation criterion	Weighting-factor
Level of detail of description of methods	0.09
Level of detail and reliability of data source	0.11
Information content of geometric and structural parameters	0.16
Availability of simulation data	0.13
Availability of aeroelastic model	0.11
Availability of CAD model	0.04
Availability and usability of blade design information	0.16
Availability and usability of controller information	0.09
Availability of further literature	0.04
Possibility to contact scientific specialists and experts	0.07
Sum	**1.00**

Table 21: Weighting-factors (Comparison of 20 MW turbines)

6.3.3 Comparison / Evaluation process

For the comparison / evaluation the same procedure and the same evaluation scale with points from 0 to 4 according to the VDI 2225 are to be used. The Technical Value W_t is calculated for both turbines. As already mentioned, this method was substantial described in Chapter 4.2.3. In the following form the corresponding evaluation criteria and weighting-factors were entered and the evaluation was done. The results were highlighted.

Comparison / Evaluation of 20 MW turbines

Problem: sheet-no.: 1 / 1

Recommendation of 20 MW turbine for future work

Turbines / Evaluation criteria	Factor	UpWind 20 MW Wind Turbine		Upscaled DTU 20 MW Turbine	
	∑ = 1	Points	Weighted Points	Points	Weighted Points
Level of detail of description of methods	**0.09**	2	0.18	3	0.27
Level of detail and reliability of data source	**0.11**	3	0.33	3	0.33
Information content of geometric and structural parameters	**0.16**	3	0.48	4	0.64
Availability of simulation data	**0.13**	2	0.26	3	0.39
Availability of aeroelastic model	**0.11**	1	0.11	1	0.11
Availability of CAD model	**0.04**	2	0.08	3	0.12
Availability and usability of blade design information	**0.16**	3	0.48	3	0.48
Availability and usability of controller information	**0.09**	2	0.18	2	0.18
Availability of further literature	**0.04**	3	0.12	4	0.16
Possibility to contact scientific specialists and experts	**0.07**	3	0.21	3	0.21
Sum of points	**1.00**	**24**	**2.43**	**29**	**2.89**
Maximum points	-	40	4.00	40	4.00
Technical Value W_t [%] (= ratio to maximum points)	**-**	**60.0**	**60.75**	**72.5**	**72.25**
Rank	**-**	**2**	**2**	**1**	**1**

Comments with indication of the turbine name:

Both Turbines	Minimum Technical Value W_t of 60 % are reached.
UpWind 20 MW Wind Turbine	Minimum Technical Value W_t is only slightly exceeded.
Upscaled DTU 20 MW Turbine	Technical Value W_t exceeds the value of the UpWind turbine.
Result	**Under consideration of availability of data, in this context, the upscaled DTU 20 MW turbine is better.**

Evaluation scale:	0 – unsatisfactory, 1 – just tolerable, 2 – adequate, 3 – good, 4 – very good
Weighting-factors:	Decimal values between 0 and 1, which are overall summed to 1
Acceptable turbine:	Technical Value W_t ≥ 60 %, otherwise check turbine and/or evaluation!

Table 22: Form sheet – Comparison of 20 MW turbines

Following the form, at this point it is described, how the respective points have been assigned. So, when looking at the first criterion "level of description of methods" the upscaled DTU 20 MW turbine is higher rated, because of the very detailed description of the methods within the reports [22] and [24] of the 10 MW starting turbine. In contrast to this the final report of the UpWind 20 MW turbine (see [8]) is, as already mentioned, formulated very superficially. Merely the pre-design report [17] is very detailed. With regard to the "level of detail and reliability of data source" both turbines, respectively the reports of both turbines are equivalent. The reliability of both turbines is good. Furthermore, the "information content of geometric and structural parameters" of the upscaled DTU 20 MW turbine is very good, because most of the data was comprehensible generated within this thesis. On the other hand, the information content of the parameters of the UpWind 20 MW turbines is also good. All in all, the geometric and structural parameters are of high quality.

When looking at the "availability of simulation data" tables of simulation results are existing for both turbines. Overall, for the upscaled DTU 20 MW turbine, respectively the 10 MW starting turbine more data is available, so that this turbine was rated higher. An aeroelastic model is probably available for both turbines, but it is unknown in this context. As a consequence, the turbines are evaluated as just tolerable. The situation is similar, when considering the CAD models. For both turbines, a CAD model exists indeed, but for the UpWind 20 MW turbine it is unknown and for the upscaled DTU 20 MW turbine the grade of detail is, as already mentioned, inadequate. However, in this context, the model of the upscaled DTU 20 MW turbine was higher rated. Furthermore, at this point, the comparatively low weighting-factor is to be mentioned. In general, for further analyzes the aeroelastic model is of higher relevance.

The "availability and usability of blade design information" was again rated as equivalent for both turbines. The information is given within several tables for both turbines. The same is true for the "availability and usability of controller information". For the criterion "availability of further literature" again the upscaled DTU 20 MW turbine was rated higher. The turbine was rated as very good, whereas the UpWind 20 MW turbine was rated as good. This is because for the former turbine a large set of data, including tables of parameters, simulation data and models, is available. The data set is more comprehensive, when comparing to the UpWind 20 MW turbine.

Last but not least the “possibility to contact scientific specialists and experts” is to be rated as equivalent for both turbines. For example, the names of the authors can be found in the respective reports (see [8], [17], [22], [24]), and can be used as starting point for an online search. For this reason, both turbines were evaluated as good.

Finally, the next chapter will focuses on the results of the comparison / evaluation.

6.4 Results of comparison

This chapter summarizes the results of the three different types of comparison / evaluation, which were done before.

First of all, when looking at the comparison by pros and cons, these are mostly balanced. For both turbines there are the same number of pros and cons (UpWind 20 MW Wind Turbine: four pros and cons; upscaled DTU 20 MW Turbine: five pros and cons). In terms of content, there are no major differences between the UpWind 20 MW turbine and the upscaled DTU 20 MW turbine.

Second, when looking at the parameters of both turbines, these are relatively similar to each other. As described above this is due to the fact, that both turbines are based on the same 5 MW reference turbine. But it is to be noted, that the UpWind 20 MW turbine is an optimized wind turbine, whereas the upscaled DTU 20 MW turbine is only a “theoretical” turbine, based on classical upscaling laws and relations, which parameters has not been checked yet.

And as last point, the results of the evaluation: In general, both turbines achieve the minimum required Technical Value W_t of 60 %. This means, that both turbines are theoretically usable for further research studies. However, the achieved values of both turbines are not good, because the minimum value has just been exceeded (UpWind 20 MW turbine: 60 % without weighting and 60.75 % when weighting-factors are included; upscaled DTU 20 MW turbine: 72.5 % without weighting and 72.25 % when weighting-factors are included). In respect to this, values of over 80 % are necessary, to achieve a very good result (see Table 14). As it can be seen, the Technical Value W_t of the upscaled DTU 20 MW turbine is higher of that of the UpWind 20 MW turbine. This is largely due to the fact, that there is less data (simulation, controller, etc.) of the UpWind 20 MW turbine available. What is also noticeable is that only minor differences between the weighted case and the non-weighted case exist. Thus, the use of weighting-factors in this case does not have any effect on the result. Finally, it is to be noted, that the whole evaluation depends on the data, which was described within this thesis. So, the evaluation is to be repeated, if more data is available, for example from further studies.

6.4.1 Conclusion of comparison

Under the consideration of the three different comparisons before, no clear optimum has been found. Although the evaluation results the upscaled DTU 20 MW turbine as the better turbine, the turbine cannot be clearly recommended. This is because, with regard to further studies, only the UpWind 20 MW turbine is an optimized 20 MW wind turbine (whose parameters are determined several times due to different simulations), whereas the parameters of the upscaled DTU 20 MW turbine are only “theoretical” and not optimized or checked. So overall, a combination of both turbines would be ideal. The parameters of the UpWind 20 MW turbine could be, as the case may be, supplemented by some parameters of the upscaled DTU 20 MW turbine. This means, that maybe it is useful to assume especially parameters, which are unknown or not trustworthy (for example due to unknown origin or method). This approach is possible, because both turbines based on the same reference turbine. It could improve the design of the UpWind 20 MW turbine. Furthermore, extensive data would be available for further studies.

6.4.2 Recommendation for the future work

As a consequence of the conclusion in the chapter before, unfortunately no precise recommendation can be made for future work. The turbines have both advantages and disadvantages. Taking all three comparisons into account, overall, the use of the UpWind 20 MW turbine is suggested, because most of the parameters are verified. As mentioned before, some parameters could be assumed by the parameters of the upscaled DTU 20 MW turbine. Furthermore, it is important to organize more “original” data of the UpWind 20 MW turbine, for example by contacting scientific specialists.

Contrary to this suggestion, another possibility is to improve the parameters of the upscaled DTU 20 MW turbine independently. Considering that, load and CFD simulation have to be done. The disadvantage is a very high effort of work. Taking the effort into account, the advantages of this approach have to be critically looked at. Finally, one option has to be chosen. Possibly a combination of both turbines, as mentioned in the chapter before, would be the best choice.

Chapter 7

Summary and outlook

7.1 Summary of the thesis

The aim of this thesis was to do a comparison of at least two future (20 MW) three-bladed offshore wind turbines, with a focus on the question of suitability for use as 20 MW reference turbines for upcoming research projects at HAW Hamburg. Therefore, some important theoretical fundamentals for the future consideration of wind turbines with a maximum rated power output of 20 MW were treated.

The issues from scientific background, which are considered at first, are the history of wind turbines for the purpose of energy production, the design of modern wind turbines, the UpWind project as a possible view of the future and the explanation of upscaling laws and relations. As a result, it can be registered, that today's wind turbines differ only slightly in their functionality. With respect to the main components, there are some options which are nowadays common, for example different blade material or different drive train concepts. The UpWind project shows, that wind turbines with a maximum rated power output of 20 MW are feasible for the future. When creating such a big turbine, for example due to upscaling, three laws have to be observed. In compliance with these, a few relations can be formulated and applied accordingly. Other length and parameters, which do not depend on laws and relations, can be upscaled by using a standardized factor q. In the context of theoretical upscaling, the knowledge of current scientific literature was also picked up, to see historical trends. In general, the trends are to be seen critically. All data and all trend lines depend on the perception of the respective scientific studies, so that it is difficult to differentiate between real scaling trends and effects of technology improvements.

This thesis gave a good overview of the latest State of the Art turbines, with view of the continuing development and grow up of wind turbines. In this context, State of the Art turbines means turbines with a maximum rated power output of ≥ 10 MW (research purposes) and ≥ 8 MW (energy production purposes). By the use of a literature research, three turbines for research purposes (UpWind 20 MW Wind Turbine, Azimut Offshore Wind Energy 15 MW wind turbine and DTU 10 MW Reference Turbine), four turbines for the purpose of energy production (AMSC wt10000dd SeaTitan^{TM}, MHI Vestas Offshore V164-9.0 MW, Siemens Wind Turbine SWT-8.0-154 and Adwen AD 8-180) and one turbine, which is not classifiable (Sway Turbine ST 10), could be found. A total of five of these turbines are theoretically suitable for upscaling (all turbines without Azimut turbine and Sway turbine; UpWind turbine is still scaled to 20 MW rated power). To evaluate these turbines and finally to select one turbine for upscaling, the standardized method according to VDI 2225 was applied. After a comprehensive explanation of the evaluation process, the description of the evaluation criteria and the allocation of the weighting-factors, the DTU 10 MW Reference Turbine was selected for upscaling.

The practical usage of the upscaling process was carried out. For this, lengths, diameters, velocities, masses and inertia as well as further parameters were adapted according to the upscaling laws and relations. As a result, the DTU 10 MW Reference Turbines was upscaled to a 20 MW turbine. The results are a first approximation of critical operational and structural properties. The parameters are not optimized and not checked due to load and aerodynamic simulations. The whole turbine is the product of classical upscaling and is only "theoretical". To finish the design of the upscaled DTU 20 MW turbine further aspects have also been considered. This included the implementation of the knowledge from current scientific literature, in this context some approaches for weight reduction of the turbine components, based on the (critically) historical trends. Another result is a CAD model of the 20 MW system.

Finally, a comprehensive comparison of two 20 MW turbines was realized. The upscaled DTU 20 MW turbine was compared with the UpWind 20 MW turbine. At first, the pros and cons of the individual turbines were compared. Overall, these are mostly balanced. Subsequently, the technical and structural parameters of the two turbines were compared by listing them in a table. Because both turbines are based on the same 5 MW reference turbine, the parameters are relatively similar to each other. At last an objective evaluation of the two turbines was carried out again according to the standardized method of VDI 2225, similar to the selection of a turbine for upscaling. The upscaled DTU 20 MW turbine reached rank 1 with a Technical Value W_t of 72.25 %, when weighting-factors included. The UpWind 20 MW turbine reached a Technical Value of 60.75 %. All in all, the achieved values of both turbines are not good, so it was difficult to give a clear recommendation for upcoming research projects. The conclusion is summarized in the last chapter of this thesis.

7.2 Conclusion and outlook for further research

In conclusion, the thesis is a profound starting point for further research studies at HAW Hamburg. The question of possible reference turbine was looked at closer. Overall, no clear optimum has been found. The turbines have both advantages and disadvantages. Finally, the use of the UpWind 20 MW turbine for further research purpose can be recommended. If necessary, missing parameters can be supplemented by parameters of the upscaled DTU 20 MW turbine. In this case a verification for example due to simulations is required. Another possibility is to improve the parameters of the upscaled DTU 20 MW turbine independently and without consideration of the UpWind 20 MW turbine. As a consequence, also load and CFD simulation have to be done, to verify the result. Depending on which option was chosen, an outlook can be made:

The next step following this thesis is to extend and to improve the structural and technical parameters of at least one turbines (depending on the chosen option of the recommendation), or if applicable both turbines. Because a detailed research for information was already done, it could be useful to concentrate on contacting experts, who could answer specific questions. In addition, a closer analysis of the blades and of the controller should be done, because this information is of decisive importance for further studies. In this context, the aeroelastic models and CAD models, if available, should also be revised. If necessary, simulations could be made, again to improve the parameters, but therefore the general data availability is to be checked. Overall, the aim of further research is to answer the question on a possible 20 MW reference turbine more precisely, respectively to underline the results of this thesis.

References

[1] International Energy Agency, "Renewables", 2017. [Online]. Available: https://www.iea.org/topics/renewables/. [Accessed 25 April 2017].

[2] E. Hau, Windkraftanlagen: Grundlagen, Technik, Einsatz, Wirtschaftlichkeit (German Edition), Springer Vieweg, 2014.

[3] A. Betz, Wind-Energie und ihre Ausnutzung durch Windmühlen, Vandenhoekk and Rupprecht, 1926.

[4] T. Burton, N. Jenkins, D. Sharpe and E. Bossanyi, Wind Energy Handbook, Wiley John + Sons, 2011.

[5] J. F. Manwell, J. G. McGowan and A. L. Rogers, Wind Energy Explained, Wiley John + Sons, 2010.

[6] P. C. Putnam, Power from the Wind, Van Nostrand Reinhold Inc.,U.S., 1982.

[7] R. Gasch and J. Twele, Windkraftanlagen: Grundlagen, Entwurf, Planung und Betrieb (German Edition), Springer Vieweg, 2013.

[8] N. Fichaux, J. Beurskens, P. H. Jensen and J. Wilkes, "UpWind: design limits and solutions for very large wind turbines-A 20MW turbine is feasible", *UpWind final report,* 2011.

[9] The European Wind Energy Association, "UpWind", [Online]. Available: http://www.ewea.org/our-activities/eu-funded-projects/completed-projects/upwind/. [Accessed 4 May 2017].

[10] Bundesministerium für Wirtschaft und Energie, "Erneuerbare Energien", 2017. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Dossier/erneuerbare-energien.html. [Accessed 27 April 2017].

[11] WindEurope, "Wind in power - 2016 European statistics", 2017.

[12] INNWIND project team, "About INNWIND.EU", [Online]. Available: http://www.innwind.eu/about-innwind. [Accessed 1 May 2017].

[13] P. Jamieson, "Multi Rotors - a Solution to 20 MW and Beyond?", in *Woche der Energie 2013*, Hamburg, 2013.

[14] P. Jamieson, Innovation in Wind Turbine Design, JOHN WILEY & SONS INC, 2011.

[15] G. Sieros, P. Chaviaropoulos, J. D. Sørensen, B. H. Bulder and P. Jamieson, "Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy", *Wind energy,* vol. 15, pp. 3-17, 2012.

[16] P. Gardner, A. Garrad, L. F. Hansen, P. Jamieson, C. Morgan, F. Murry and A. Tindal, "Wind Energy - The Facts (Part I) - Technology", *Wind Energy - The Facts,* 2009.

[17] J. Peeringa, R. Brood, O. Ceyhan, W. Engels and G. de Winkel, "UpWind 20MW Wind Turbine Pre-Design", *ECN, Paper No. ECN-E--11-017,* 2011.

[18] J. Jonkman, S. Butterfield, W. Musial and G. Scott, "Definition of a 5-MW reference wind turbine for offshore system development", National Renewable Energy Laboratory, 2009.

[19] Siemens AG Press, "Merger of Siemens Wind Power and Gamesa", 2017. [Online]. Available: https://www.siemens.com/press/en/events/2016/corporate/2016-06-telefonkonferenz.php. [Accessed 22 June 2017].

[20] Gamesa, "Azimut Offshore Wind Energy 2020 project", [Online]. Available: http://www.gamesacorp.com/en/products-and-services/wind-turbines/rd/id-principales-proyectos.html. [Accessed 15 May 2017].

[21] Gamesa, "Ending of the Azimut project that will enable the development of a 15 MW offshore wind turbine in 2020", 2014. [Online]. Available: http://www.gamesacorp.com/en/communication/news/ending-of-the-azimut-project-that-will-enable-the-development-of-a-15-mw-offshore-wind-turbine-in-2020.html?idCategoria=60. [Accessed 15 May 2017].

[22] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. C. Henriksen, M. H. Hansen, J. P. A. A. Blasques, M. Gaunaa and A. Natarajan, "The DTU 10-MW reference wind turbine", *Danish wind power research,* 2013.

[23] C. Bak and F. Zahle, "The DTU 10 MW Reference Wind Turbine", in *Science Meets Industry, Bergen*, 2015.

[24] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. C. Henriksen, A. Natarajan and M. H. Hansen, "Description of the DTU 10 MW Reference Wind Turbine", *DTU Wind Energy Report-I-0092,* 2013.

[25] American Superconductor Corp., "SeaTitan 10 MW Wind Turbine", American Superconductor Corp., 2012.

[26] wind-turbine-models.com, "AMSC wt10000dd SeaTitan", 2013. [Online]. Available: https://en.wind-turbine-models.com/turbines/425-amsc-wt10000dd-seatitan. [Accessed 18 May 2017].

[27] MHI Vestas Offshore Wind, "A strategic commitment to affordable offshore wind power", [Online]. Available: http://www.mhivestasoffshore.com/about-mhi-vestas-offshore/. [Zugriff am 29 May 2017].

[28] MHI Vestas Offshore Wind, "Worldś most powerful wind turbine once again smashes 24 hour power generation record as 9 MW wind turbine is launched", [Online]. Available: http://www.mhivestasoffshore.com/new-24-hour-record/. [Zugriff am 29 May 2017].

[29] wind-turbine-models.com, "MHI Vestas Offshore V164-9.0", 2017. [Online]. Available: https://en.wind-turbine-models.com/turbines/1568-mhi-vestas-offshore-v164-9.0-mw. [Accessed 29 May 2017].

[30] Siemens Wind Power and Renewables Division, "Wind Turbine SWT-8.0-154 Technical specifications", Siemens AG, 2016.

[31] Siemens Wind Power and Renewables Division, "The SWT-8.0-154: Minimum upgrades, maximum effects", Siemens AG, 2016.

[32] wind-turbine-models.com, "Siemens SWT-8.0-154", 2017. [Online]. Available: https://en.wind-turbine-models.com/turbines/1465-siemens-swt-8.0-154. [Accessed 17 May 2017].

[33] J. Vollrath, *Technische Daten Siemens SWT-8.0-154,* Technische Daten Siemens SWT-8.0-154: [E-Mail], jan.vollrath@siemens.com, 05 May 2017.

[34] ADWEN, "8 MW Platform", [Online]. Available: http://www.adwenoffshore.com/de/products-services/products/8-mw-turbines/. [Accessed 08 June 2017].

[35] wind-turbine-models.com, "Adwen AD 8-180", 2015. [Online]. Available: https://en.wind-turbine-models.com/turbines/1124-adwen-ad-8-180. [Accessed 29 May 2017].

[36] ADWEN, "Adwen and LM Wind Power Partner to present the longest blade in the world", [Online]. Available: http://www.adwenoffshore.com/de/adwen-and-lm-wind-power-partner-to-present-the-longest-blade-in-the-world-2/. [Accessed 08 June 2017].

[37] www.swayturbine.no, "Principles of the Sway Turbine System", [Online]. Available: http://www.swayturbine.no/?page=219. [Accessed 13 June 2017].

[38] E. Borgen, "Drivetrain Concepts for Wind Turbines", in *IQPC 3rd International Conference*, Bremen, 2012.

[39] E. de Vries, "Close up - Sway Turbineś ST10 10 MW turbine", 2012. [Online]. Available: http://www.windpowermonthly.com/article/1155881/close---sway-turbines-st10-10mw-turbine. [Accessed 13 June 2017].

[40] E. Spooner, P. Gordon, J. R. Bumby and C. D. French, "Lightweight ironless-stator PM generators for direct-drive wind turbines", *IEE Proceedings-Electric Power Applications,* vol. 152, pp. 17-26, 2005.

[41] T. Werner, "Identifizierung und Bewertung von Triebstrangkonzepten für Windenergieanlagen", *Masterproject at the University of Applied Science Hamburg,* 2014.

[42] Verein Deutscher Ingenieure, "VDI 2225: Technisch-wirtschaftliches Konstruieren", *VDI-Richtlinien,* 1998.

[43] H. Frohne, K.-H. Löcherer and H. Müller, Moeller Grundlagen der Elektrotechnik (Leitfaden der Elektrotechnik), Vieweg + Teuber Verlag, 2005.

[44] V. Schorbach, Pendelendanschläge bei Zweiblatt-Windenergieanlagen, VDI Verlag GmbH, 2016.

[45] Det Norske Veritas - Germanischer Lloyd, "DNV GL in brief", [Online]. Available: https://www.dnvgl.com/about/index.html. [Accessed 18 July 2017].

[46] International Electrotechnical Commission, "Developing International Standards", [Online]. Available: http://www.iec.ch/about/activities/standards.htm. [Accessed 18 July 2017].

[47] The Knowledge Centre Wind turbine Materials (WMC), "FOCUS6: The integrated Modular Wind Turbine Design Tool", 2017. [Online]. Available: http://www.wmc.eu/pdf/WMC_focus6_2017.pdf. [Accessed 5 May 2017].

[48] Siemens Wind Power, "IntegralBlade: A key technology unique to the wind industry", Siemens AG, 2012.

Appendix

I. Scaling trends from current scientific literature

i. Nacelle mass

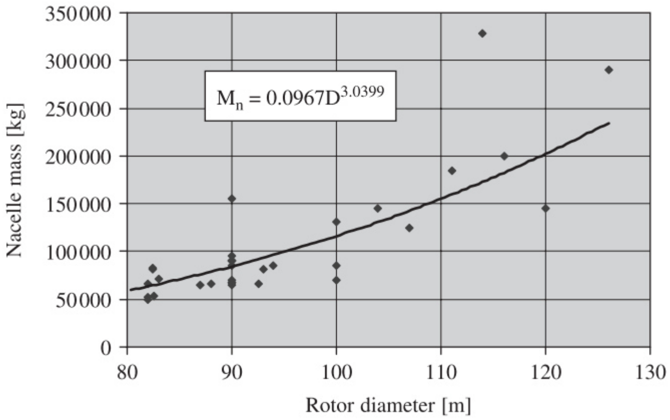

Figure A-01: Nacelle mass trends, (Source: [14])

ii. Tower top mass

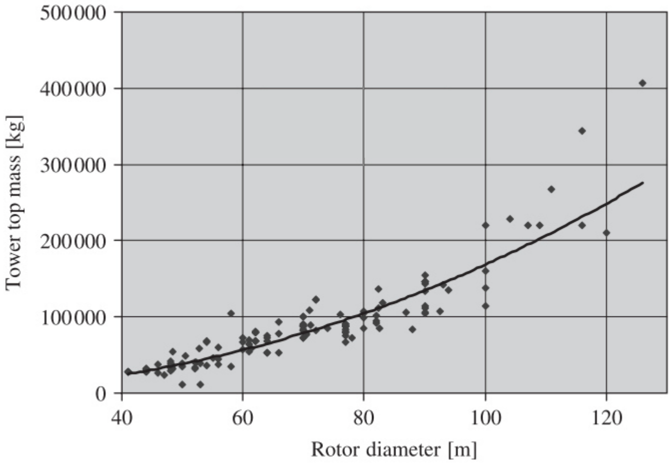

Figure A-02: Tower top mass trends, (based on [14])

iii. Tower mass

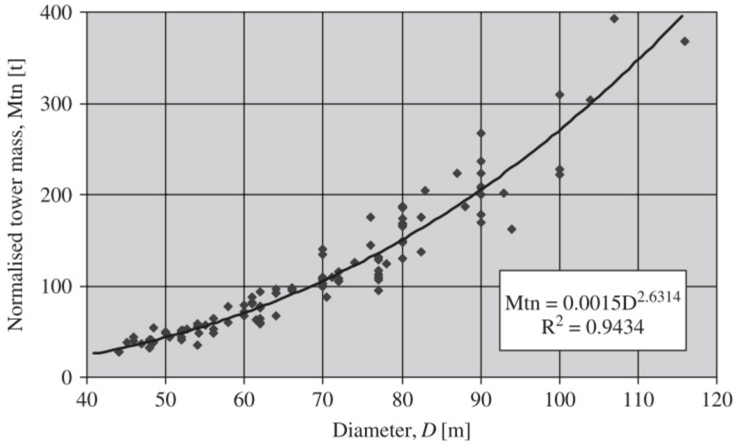

Figure A-03: Normalised tower mass trends, (Source: [14])

iv. Tower base moment M_x

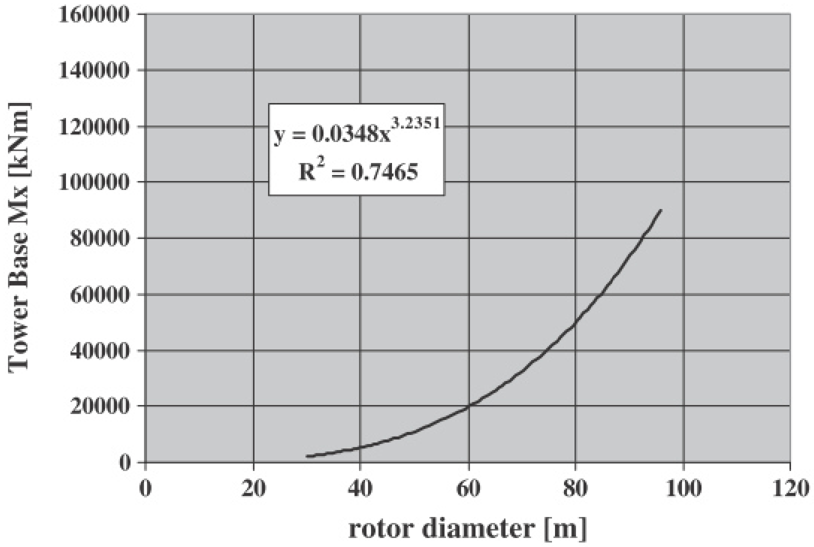

Figure A-04: Tower base roll moment M_x trends, (Source: [15])

v. Tower base moment M_y

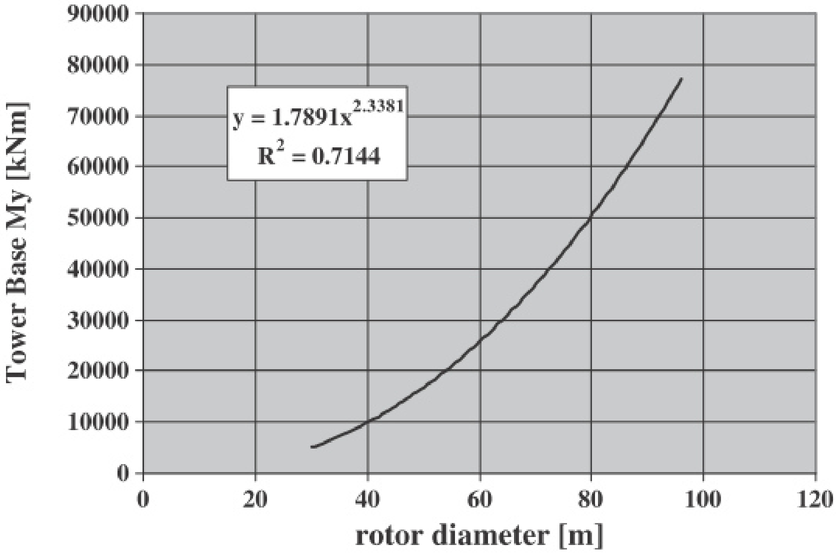

Figure A-05: Tower base pitch moment M_y trends, (Source: [15])

vi. Tower base moment M_z

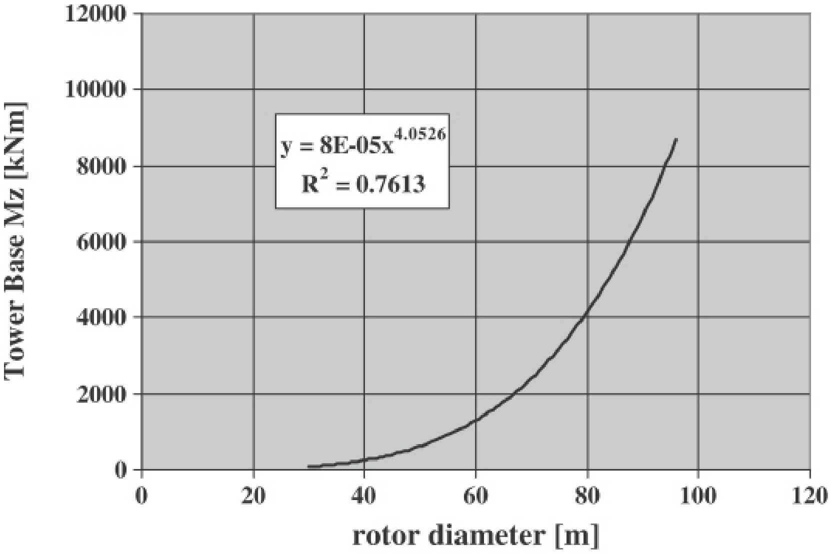

Figure A-06: Tower base yaw moment M_z trends, (Source: [15])

vii. Blade root moment M_x

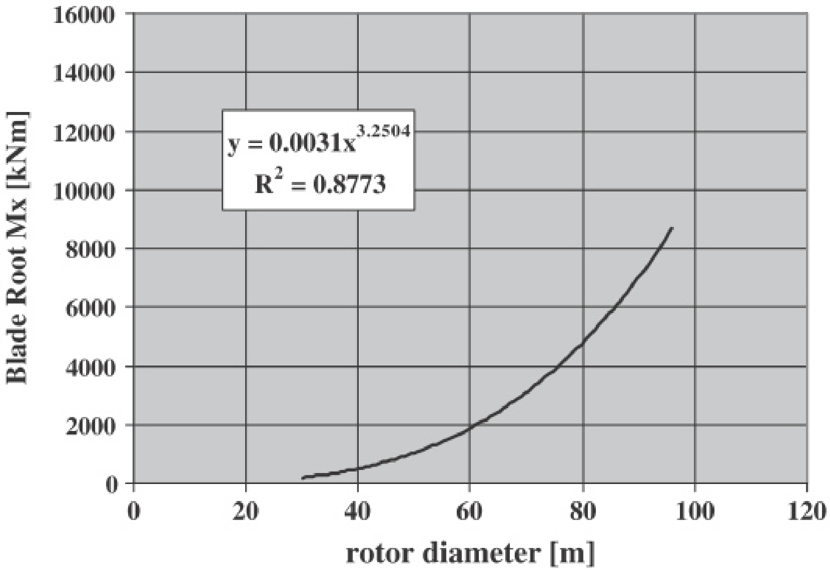

Figure A-07: Blade root roll moment M_x trends, (Source: [15])

viii. Blade root moment M_y

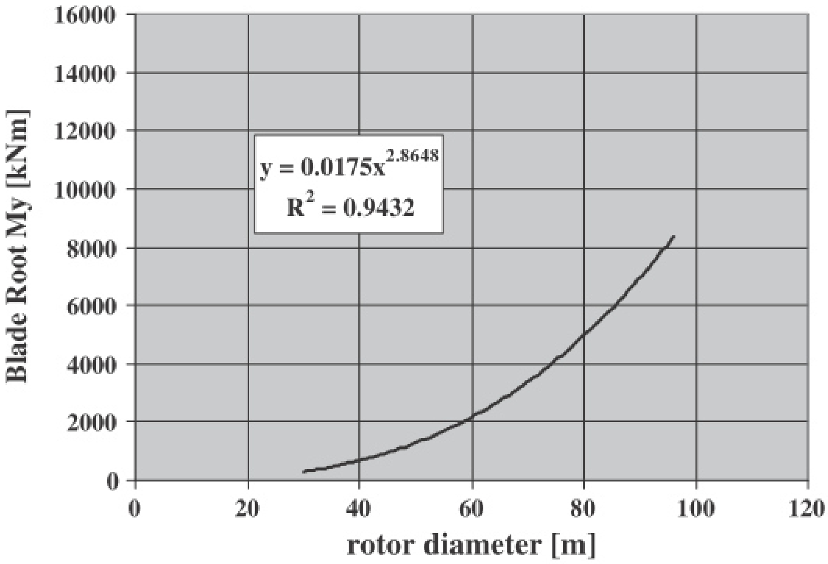

Figure A-08: Blade root pitch moment M_y trends, (Source: [15])

ix. Blade root moment M_z

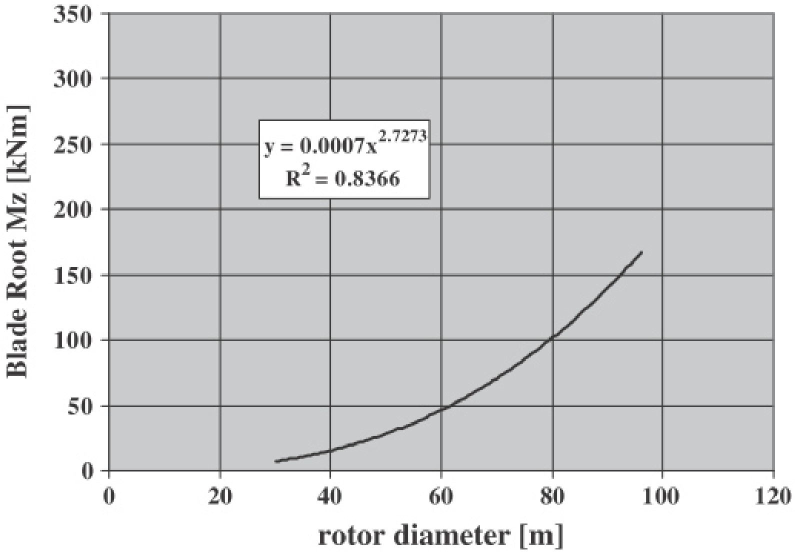

Figure A-09: Blade root yaw moment M_z trends, (Source: [15])

II. Technical specifications of wind turbines

i. UpWind 20 MW Wind Turbine

UpWind 20 MW Wind Turbine

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	20 MW
	Wind regime	IEC class	IEC class IB
	Cut-in wind speed	$v_{\text{cut-in}}$	/
	Nominal power output at	v_{rated}	10 m/s
	Cut-out wind speed	$v_{\text{cut-out}}$	25 m/s (reasoned assumption)
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	252 m
	Swept area	A_{Rotor}	49,850 m²
	Power regulation	-	Variable speed, pitch control
	Rotor tilt angle	α	5 deg
	Maximum rotor speed	Ω_{MAX}	6.05 rpm
	Minimum rotor speed	Ω_{MIN}	2.58 rpm
	Maximum tip speed	v_{Tip}	80 m/s
	Rotor mass (hub + blades)	W_{Rotor}	770 t
Blade	Blade span	L_{Span}	123 m
	Blade cone angle	β	- 2.5 deg
	Blade prebend	L_{Prebend}	Existing, but unknown
	Aerodynamic profile	-	NACA, DU, Cylinder
	Blade root radius	R_{Root}	3.0 m
	Blade material	-	Glass fiber reinforced plastic (GRP)
	Blade mass	W_{Blade}	105.2 t (calculated)
Hub	Hub diameter	D_{Hub}	/
	Hub height	H_{Hub}	153 m
	Hub mass	W_{Hub}	454.2 t
	Hub static moment	$M_{\text{Hub static}}$	4,542,400 Nm
	Hub inertia (shaft-axis)	I_{Hub}	3,709,632 kgm²
Nacelle	Nacelle length (x-axis)	$L_{\text{Nacelle x}}$	/
	Nacelle width (y-axis)	$L_{\text{Nacelle y}}$	/
	Nacelle height (z-axis)	$L_{\text{Nacelle z}}$	/
	Nacelle mass	W_{Nacelle}	1,920 t
	Nacelle inertia (Roll-axis)	$I_{\text{Nacelle Roll}}$	3,120,000 kgm²
	Nacelle inertia (Tilt-axis)	$I_{\text{Nacelle Tilt}}$	93,600,000 kgm²
	Nacelle inertia (Yaw-axis)	$I_{\text{Nacelle Yaw}}$	83,452,480 kgm²
Tower	Tower height	H_{Tower}	/
	Tower outer diam. (highest section)	$D_{\text{Tower high}}$	8.16 m
	Tower outer diam. (lowest section)	$D_{\text{Tower low}}$	12.0 m
	Tower mass	W_{Tower}	2,780 t

Table A-01: Technical specifications UpWind 20 MW Wind Turbine, full, part 1/2, (based on [8, 17])

UpWind 20 MW Wind Turbine

Class	Parameter	Symbol	Characteristic
Drive train	Gearbox type	-	Existing, but unknown
	Gearbox ratio	i	194
	Gearbox inertia	$I_{Gearbox}$	0.0 kgm²
	Generator type	-	Permanent Magnet Transversal Flux Generator, optional: other
	Generator speed	$\Omega_{Generator}$	1,173.7 rpm (calculated)
	Maximum generator torque	$Q_{Generator}$	368,000 Nm

Table A-01: Technical specifications UpWind 20 MW Wind Turbine, full, part 2/2, (based on [8, 17])

ii. DTU 10 MW Reference Turbine

DTU 10 MW Reference Turbine

Class	Parameter	Symbol	Characteristic
Operational data	Nominal power output	P	10 MW
	Wind regime	IEC class	IEC class IA
	Cut-in wind speed	v_{cut-in}	4 m/s
	Nominal power output at	v_{rated}	11.4 m/s
	Cut-out wind speed	$v_{cut-out}$	25 m/s
Rotor	Number of blades	N	3
	Rotor orientation	-	Upwind
	Rotor diameter	D	178.3 m
	Swept area	A_{Rotor}	24,950 m²
	Power regulation	-	Variable speed, pitch control
	Rotor tilt angle	α	5 deg
	Maximum rotor speed	Ω_{MAX}	9.6 rpm
	Minimum rotor speed	Ω_{MIN}	6.0 rpm
	Maximum tip speed	v_{Tip}	90 m/s
	Rotor mass (hub + blades)	W_{Rotor}	230.6 t
Blade	Blade span	L_{Span}	86.35 m
	Blade cone angle	β	- 2.5 deg
	Blade prebend	$L_{Prebend}$	3.332 m
	Aerodynamic profile	-	FFA-W3-XXX, Cylinder
	Blade root radius	R_{Root}	/
	Blade material	-	Glass fiber reinforced plastic (GRP) (reasoned assumption)
	Blade mass	W_{Blade}	41.7 t

Table A-02: Technical specifications DTU 10 MW Reference Turbine, full, part 1/2, (based on [22, 24])

DTU 10 MW Reference Turbine			
Class	**Parameter**	**Symbol**	**Characteristic**
Hub	Hub diameter	D_{Hub}	5.6 m
	Hub height	H_{Hub}	119 m
	Hub mass	W_{Hub}	105.5 t
	Hub static moment	$M_{Hub\ static}$	/
	Hub inertia	I_{Hub}	325,670 kgm²
Nacelle	Nacelle length (x-axis)	$L_{Nacelle\ x}$	10 m
	Nacelle width (y-axis)	$L_{Nacelle\ y}$	10 m
	Nacelle height (z-axis)	$L_{Nacelle\ z}$	15 m
	Nacelle mass	$W_{Nacelle}$	446.0 t
	Nacelle inertia (Roll-axis)	$I_{Nacelle\ Roll}$	/
	Nacelle inertia (Tilt-axis)	$I_{Nacelle\ Tilt}$	/
	Nacelle inertia (Yaw-axis)	$I_{Nacelle\ Yaw}$	7,326,346 kgm²
Tower	Tower height	H_{Tower}	115.63 m
	Tower outer diam. (highest section)	$D_{Tower\ high}$	5.5 m
	Tower outer diam. (lowest section)	$D_{Tower\ low}$	8.3 m
	Tower mass	W_{Tower}	628.4 t
Drive train	Gearbox type	-	Multiple-stage gearbox
	Gearbox ratio	i	50
	Gearbox inertia	$I_{Gearbox}$	/
	Generator type	-	Permanent magnet synchronous generator (PMG)
	Generator speed	$\Omega_{Generator}$	480 rpm
	Maximum generator torque	$Q_{Generator}$	/

Table A-02: Technical specifications DTU 10 MW Reference Turbine, full, part 2/2, (based on [22, 24])

III. Drive train concepts

i. Concept 1: Detached drive train concept

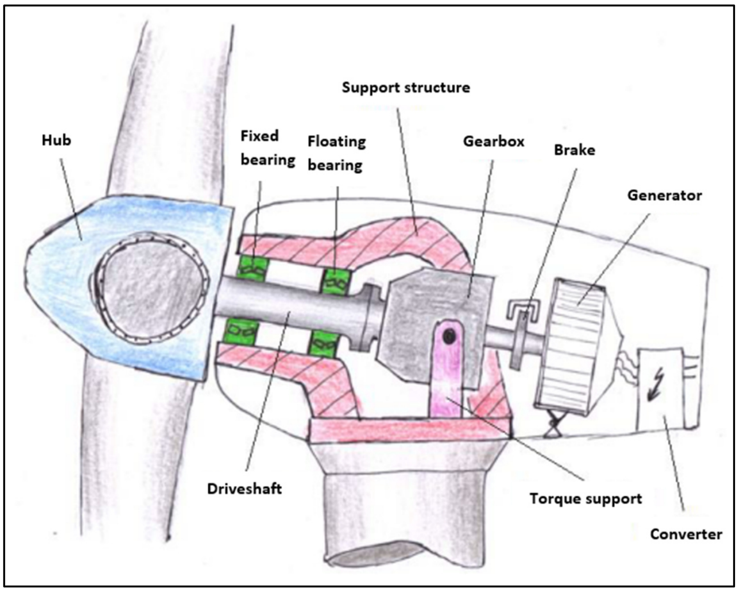

Figure A-10: Drive train concept 1 (Detached drive train), (based on [41])

Figure A-11: Example of real wind turbine (concept 1): Siemens Wind Turbine (SWT 3.6), (Source: Siemens Wind Power; available from: https://www.siemens.com/global/en/home/markets/wind/turbines-and-services/technology/nacelle.html)

ii. Concept 2: Partial integrated drive train concept

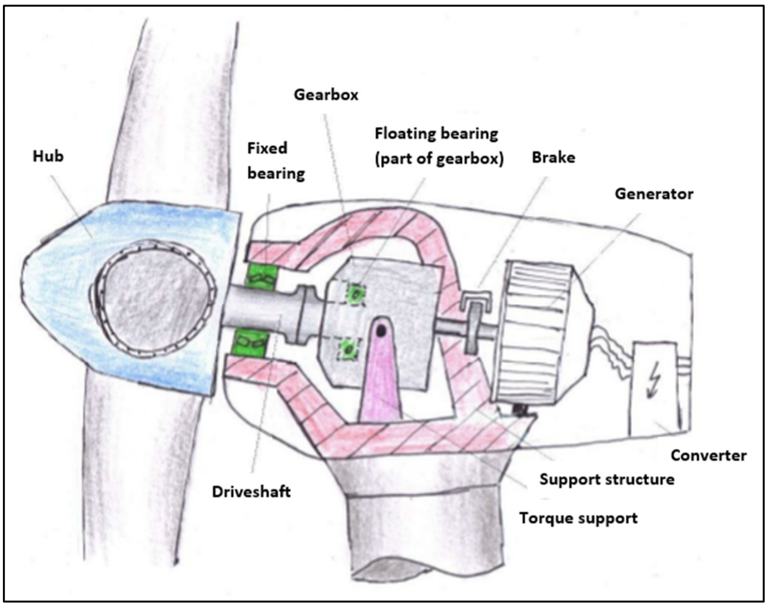

Figure A-12: Drive train concept 2 (Partial integrated drive train), (based on [41])

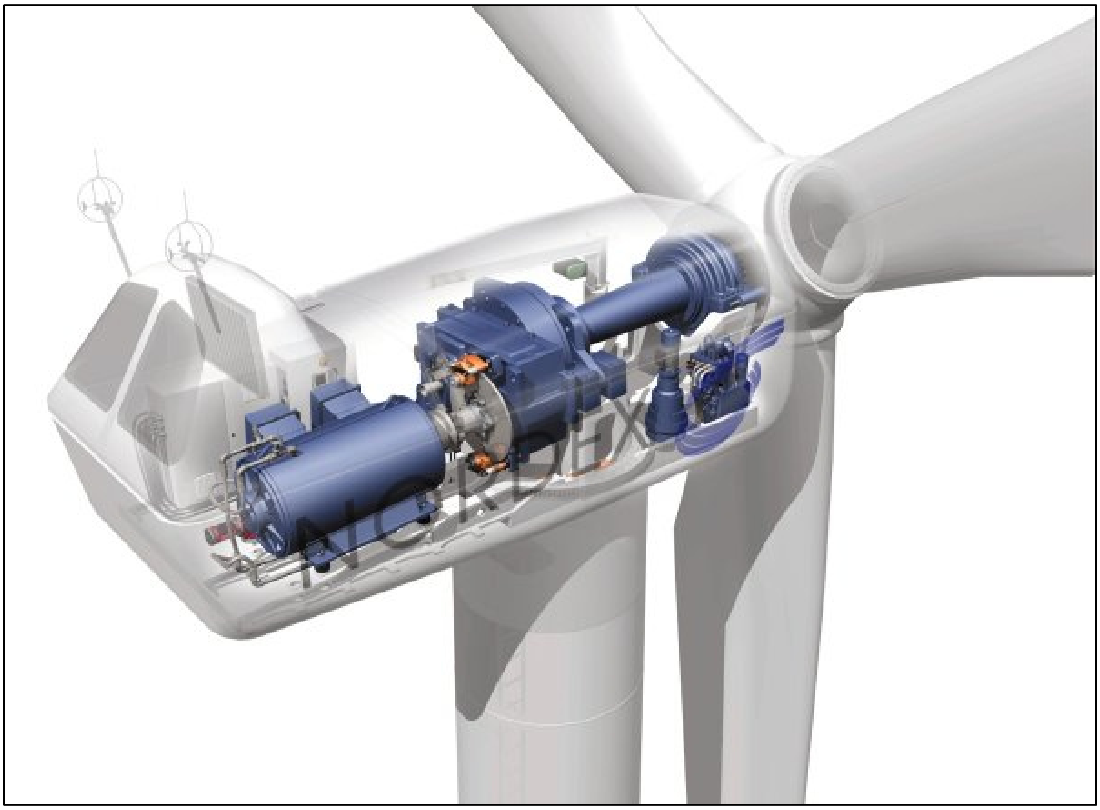

Figure A-13: Example of real wind turbine (concept 2): NORDEX Wind Turbine,
(Source: wind-energie.de; available from:
https://www.wind-energie.de/infocenter/technik/konstruktiver-aufbau/maschinenhaus-antriebstrang)

iii. Concept 3: Integrated drive train concept

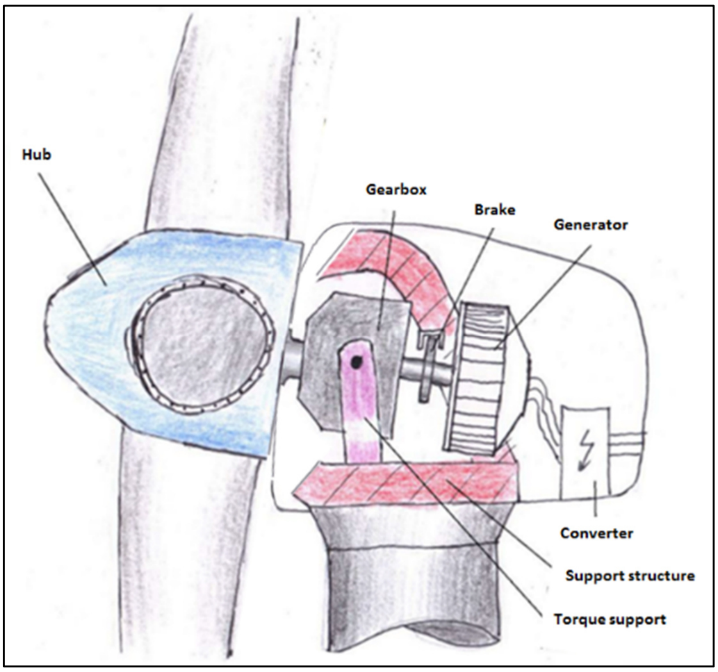

Figure A-14: Drive train concept 3 (Integrated drive train), (based on [41])

This turbine concept is out of date. It is not used by modern installations. Examples for older installations are NORDEX wind turbines with a maximum rated power of > 600 kW.[5]

---

[5] Source: https://bs-green.com/files/brands/18/nordex_3.pdf

iv. Concept 4: Torque bearing concept

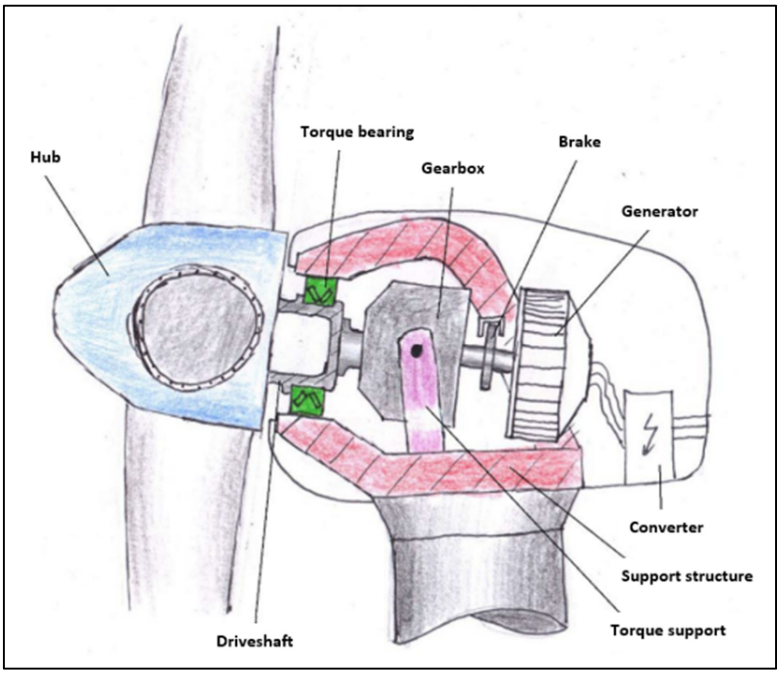

Figure A-15: Drive train concept 4 (Torque bearing concept), (based on [41])

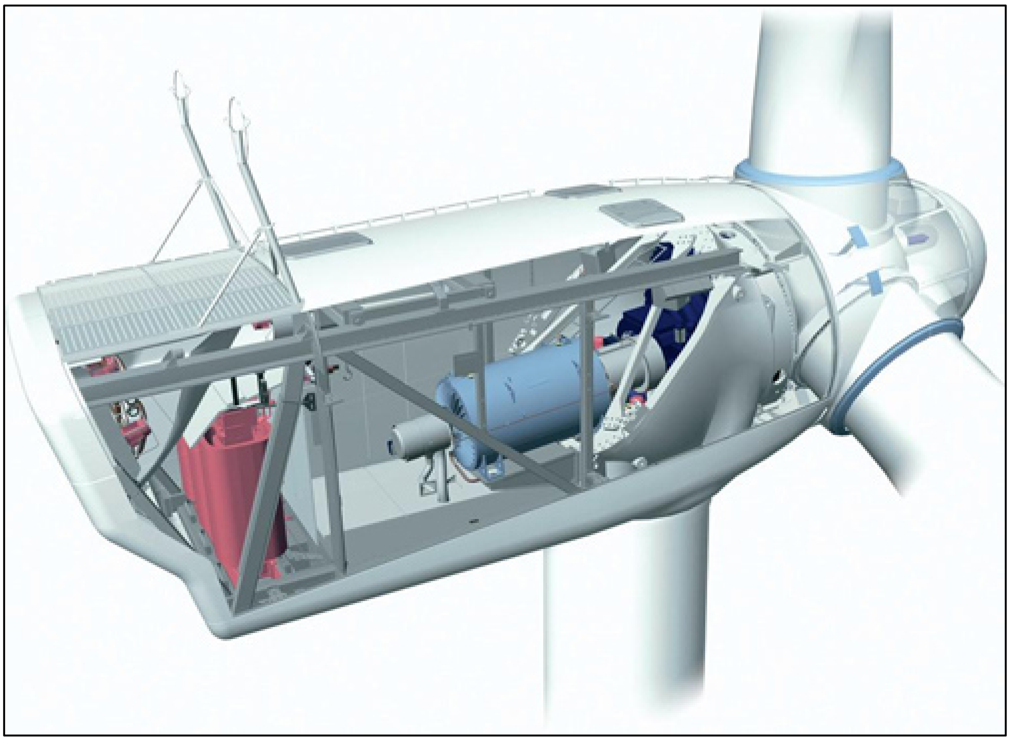

Figure A-16: Example of real wind turbine (concept 4): Vestas Wind Turbine, (Source: Wind Energy the Facts; available from: https://www.wind-energy-the-facts.org/architecture-of-a-modern-wind-turbine.html)

v. Concept 5: Bearings on kingpin concept

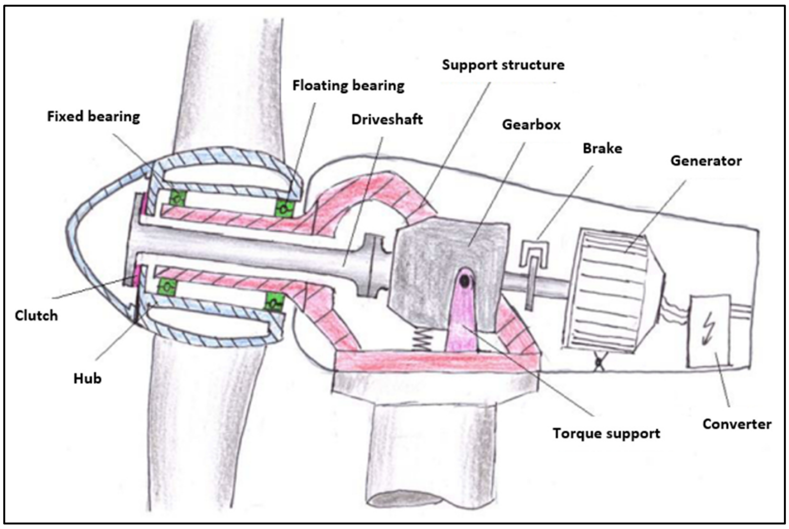

Figure A-17: Drive train concept 5 (Bearings on kingpin concept), (based on [41])

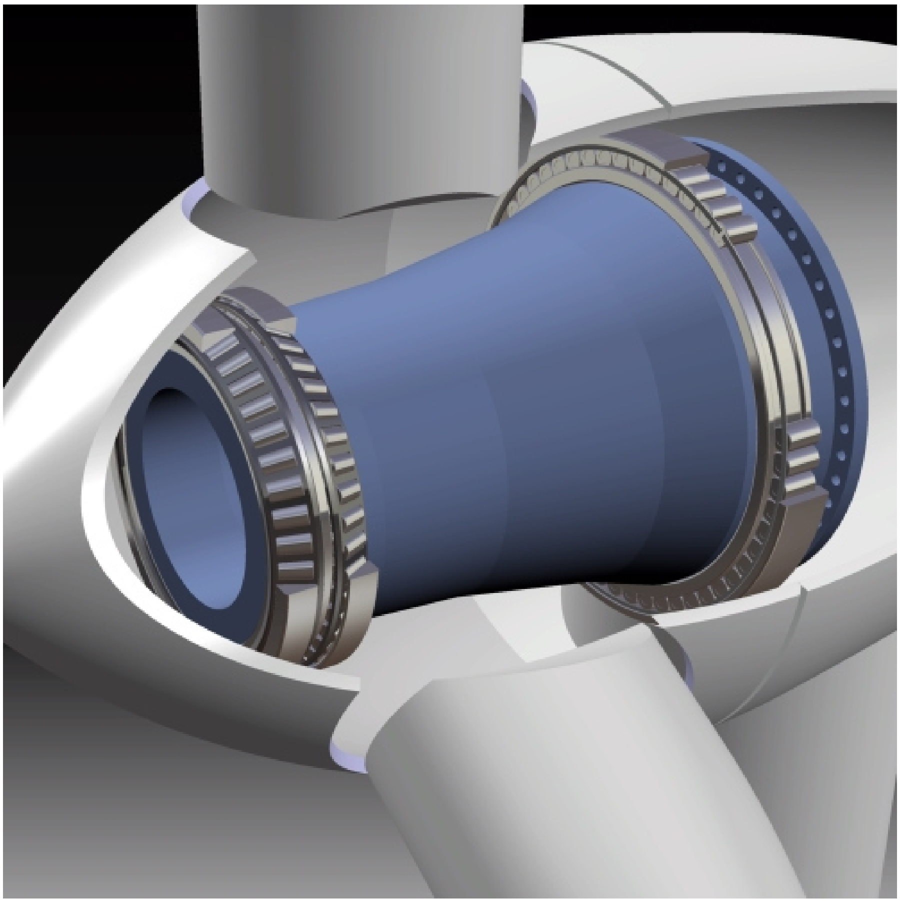

Figure A-18: Example of real wind turbine (concept 5): Alstrom (Ecotècnia) Wind Turbine, (Source: NSK-Europe; available from: http://www.nskeurope.com/wind-turbines-prevent-premature-1183.htm)

vi. Concept 6: Detached drive train concept with direct drive

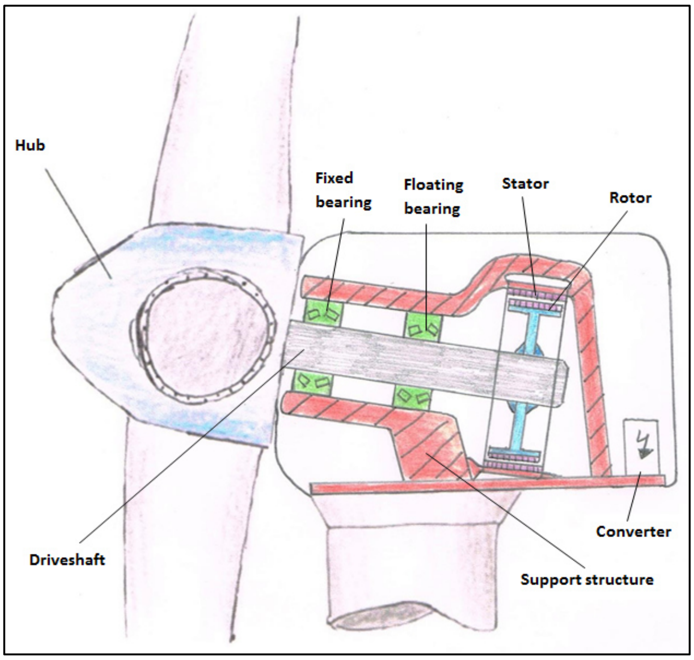

Figure A-19: Drive train concept 6 (Detached drive train with direct drive), (based on [41])

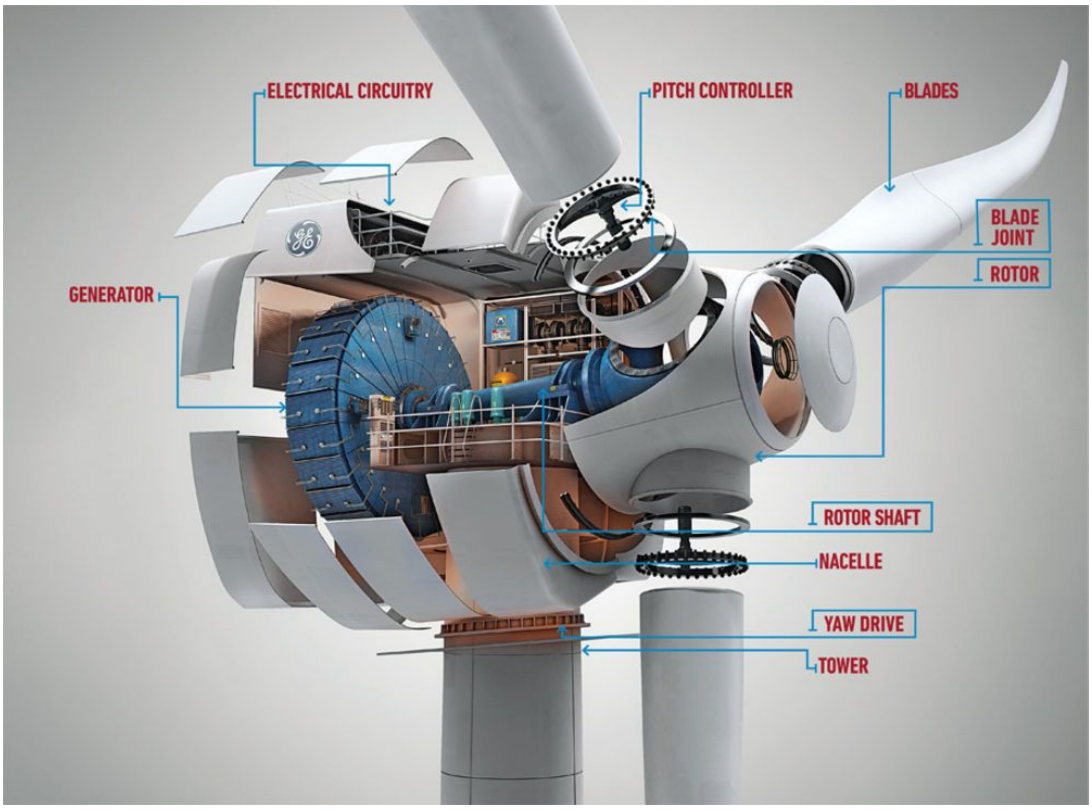

Figure A-20: Example of real wind turbine (concept 6): GE Offshore Wind Turbine,
(Source: Popsci; available from: http://www.popsci.com/content/next-gen-wind-turbine-examined)

vii. Concept 7: Integrated drive train concept with direct drive

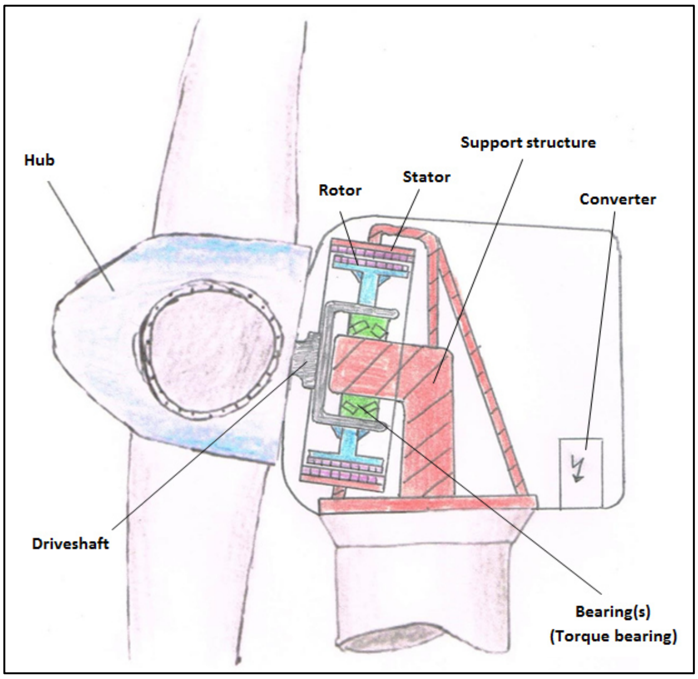

Figure A-21: Drive train concept 7 (Integrated drive train with direct drive), (based on [41])

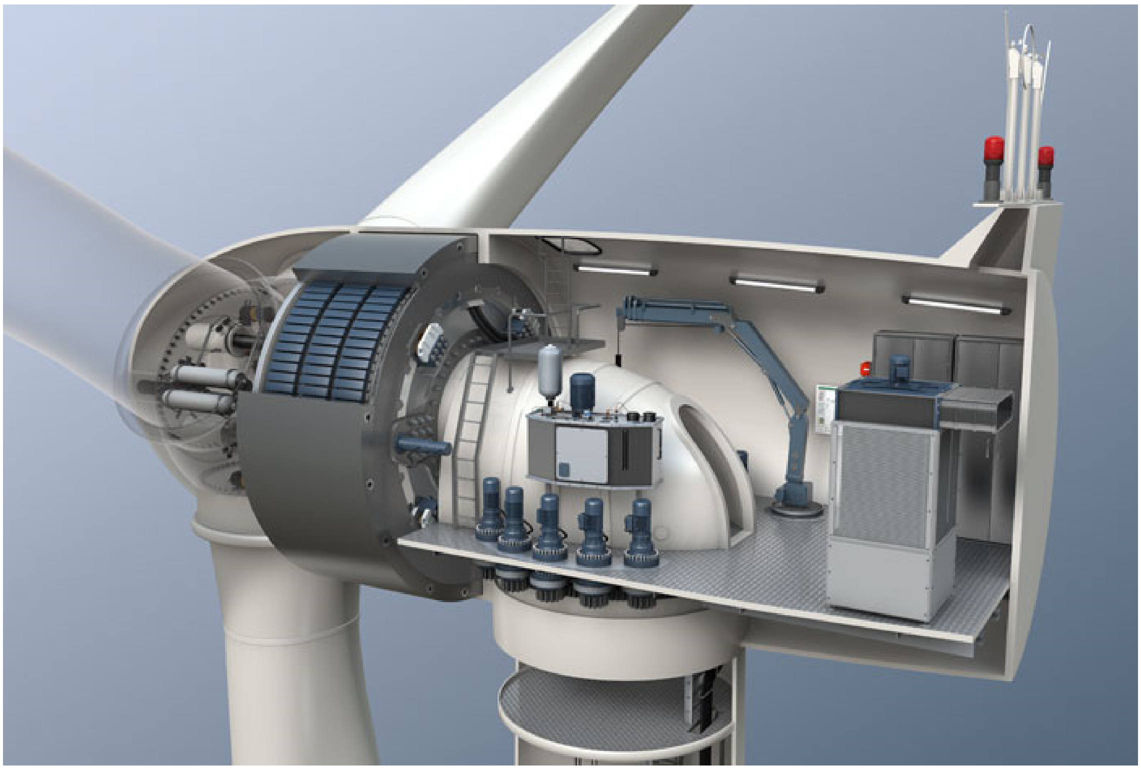

Figure A-22: Example of real wind turbine (concept 7): Siemens Wind Turbine (SWT 7.0), (Source: IFM; available from: http://www.ifm.com/ifmus/web/apps-by-industry/cat_060_010.html)

viii. Concept 8: Bearings on kingpin concept with direct drive

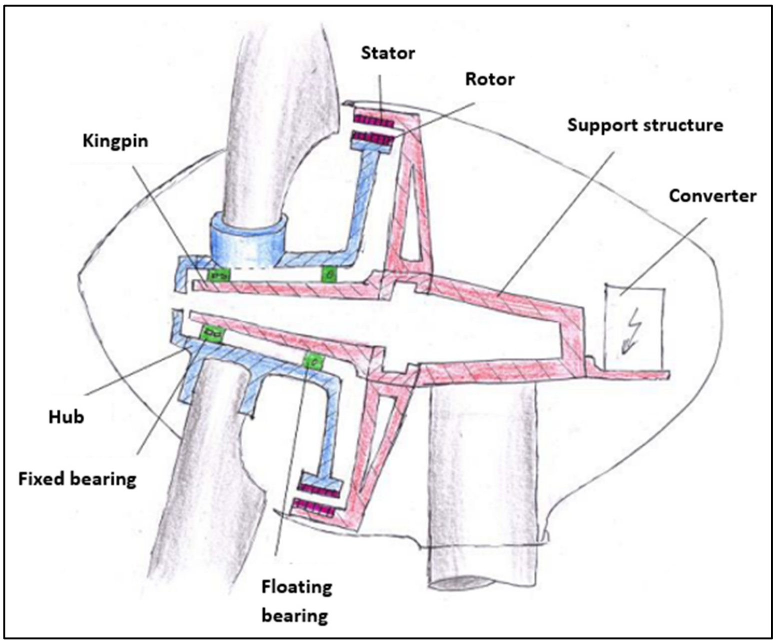

Figure A-23: Drive train concept 8 (Bearings on kingpin with direct drive), (based on [41])

Figure A-24: Example of real wind turbine (concept 8): ENERCON Wind Turbine, (Source: Windpowermonthly; available from: http://www.windpowermonthly.com/article/1289095/enercon-launch-new-high-wind-turbines)

IV. Evaluation of turbines

i. Dominance-array „Choice of turbine(s) for upscaling“

Weighting of evaluation criteria

Problem: sheet-no.: 1 / 1

Choice of turbine(s) for upscaling

Evaluation criteria	**With …**	Completeness “Operational data”	Completeness “Rotor”	Completeness “Blade”	Completen. “Hub, Nacelle, Tower”	Completeness “Drive train”	Possibility of teetering hub	Availability of turbine model	Availability of simulation data	Availability of controller information	Availability of further literature	**Count of “+”**	**Weighting factor (rounded)**
Compare …		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	-	-
Completeness “Operational data”	**1**		-	-	-	+	-	+	+	+	-	4	**0.09**
Completeness “Rotor”	**2**	+		+	+	+	-	-	+	+	-	6	**0.13**
Completeness “Blade”	**3**	+	-		+	+	-	+	+	+	-	6	**0.13**
Completeness “Hub, Nacelle, Tower”	**4**	+	-	-		+	-	-	+	+	-	4	**0.09**
Completeness “Drive train”	**5**	-	-	-	-		-	-	-	+	+	2	**0.04**
Possibility of teetering hub	**6**	+	+	+	+	+		+	+	+	+	9	**0.21***
Availability of turbine model	**7**	-	+	-	+	+	-		-	+	-	4	**0.09**
Availability of simulation data	**8**	-	-	-	-	+	-	+		+	-	3	**0.07**
Availability of controller information	**9**	-	-	-	-	-	-	-	-		+	1	**0.02**
Availability of further literature	**10**	+	+	+	+	-	-	+	+	-		6	**0.13**
Sum	**-**											**45**	**1.00**

*Due to the importance of the criterion “Possibility of teetering hub”, the weighting factor was raised from 0.2 to 0.21 to compensate the difference to the sum of 1.00. The difference resulted from the rounding of the weighting factors.

Table A-03: Dominance-array (Evaluation of turbines for upscaling)

ii. Dominance-array „Recommendation of 20 MW turbine“

Weighting of comparison / evaluation criteria

Problem: sheet-no.: 1 / 1

Recommendation of 20 MW turbine for future work

Comparison / evaluation criteria	**With …**	Level of detail of description of methods	Level of detail and reliability of data source	Inform. content of geom. / struct. parameters	Availability of simulation data	Availability of aeroelastic model	Availability of CAD model	Availability a. usability of blade design inform.	Availability a. usability of controller inform.	Availability of further literature	Possibility to contact scientific specialists and experts	**Count of "+"**	**Weighting factor (rounded)**
Compare …		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	-	-
Level of detail of description of methods	**1**		-	-	+	-	+	-	-	+	+	4	**0.09**
Level of detail and reliability of data source	**2**	+		-	-	+	+	-	-	+	+	5	**0.11**
Information content of geometric / structural parameters	**3**	+	+		-	-	+	+	+	+	+	7	**0.16**
Availability of simulation data	**4**	-	+	+		-	+	-	+	+	+	6	**0.13**
Availability of aeroelastic model	**5**	+	-	+	+		+	-	+	-	-	5	**0.11**
Availability of CAD model	**6**	-	-	-	-	-		-	+	-	+	2	**0.04**
Availability and usability of blade design information	**7**	+	+	-	+	+	+		+	+	-	7	**0.16**
Availability and usability of controller information	**8**	+	+	-	-	-	-	-		+	+	4	**0.09**
Availability of further literature	**9**	-	-	-	-	+	+	-	-		-	2	**0.04**
Possibility to contact scient. specialists and experts	**10**	-	-	-	-	+	-	+	-	+		3	**0.07**
Sum	**-**											**45**	**1.00**

Table A-04: Dominance-array (Comparison of 20 MW turbines)

Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Gemäß der Allgemeinen Prüfungs- und Studienordnung ist zusammen mit der Abschlussarbeit eine schriftliche Erklärung abzugeben, in der der Studierende bestätigt, dass die Abschlussarbeit „– bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit [(§ 18 Abs. 1 APSO-TI-BM bzw. § 21 Abs. 1 APSO-INGI)] – ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich zu machen.“

Quelle: § 16 Abs. 5 APSO-TI-BM bzw. § 15 Abs. 6 APSO-INGI

Dieses Blatt, mit der folgenden Erklärung, ist nach Fertigstellung der Abschlussarbeit durch den Studierenden auszufüllen und jeweils mit Originalunterschrift als letztes Blatt in das Prüfungsexemplar der Abschlussarbeit einzubinden.
Eine unrichtig abgegebene Erklärung kann -auch nachträglich- zur Ungültigkeit des Studienabschlusses führen.

Erklärung zur selbstständigen Bearbeitung der Arbeit

Hiermit versichere ich,

Name: Schütt

Vorname: Marcel

dass ich die vorliegende Masterarbeit bzw. bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit – mit dem Thema:

Upscaling, concept design and comparison of concepts of future three-bladed 20 MW offshore wind turbines

ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

- die folgende Aussage ist bei Gruppenarbeiten auszufüllen und entfällt bei Einzelarbeiten -

Die Kennzeichnung der von mir erstellten und verantworteten Teile der Masterarbeit ist erfolgt durch:

Hamburg	04.09.2017	
Ort	Datum	Unterschrift im Original