CHALMERS

# Wind turbine database:

*Modelling and analysis with focus on upscaling*

*Master's thesis in the Master programme Applied Mechanics*

JUAN PABLO SÁNCHEZ DE LARA GARCÍA

Department of Applied Mechanics
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## Abstract

In recent years there has been much attention to the production of electricity from wind; this is performed by wind turbines. They have been used since ancient times to produce mechanical energy with other objectives than producing electricity, like grind grains. But the real explosion, in the use of wind turbines to produce electricity, occurred from 1970 onwards, when, because of the oil crisis, new ways to produce energy were sought.

Comparing wind turbines from a decade ago and actual wind turbines, a considerable increase in the size and in the power production is observed. Building wind turbines with larger rotors allow absorbing more energy from the wind, which is why the wind turbine manufacturers are focusing on building bigger and bigger wind turbines. But this is not as easy as it seems, because creating larger turbines significantly increases the weight of all the elements and the loads. Also technological limits could appear in the production of some elements such as rotor blades. If the trends continue like in the last years, in the near future (5-10 years) blades longer than a football field might be needed.

This thesis focuses on the study of how this growth in the size of wind turbines, called Upscaling, has been done and draws conclusions on what to expect in the near future. First a database of diverse wind turbine designs is created. This database includes more than 230 different wind turbines from 34 manufacturers with a power output between 0.1 and 15 MW and a rotor diameter between 12.8 and 200 m. The database includes wind turbines that are already in the market and those which are being developed. The database also differentiates the type of drive train system in the wind turbine: geared, direct or hybrid drive train systems. This database is analysed in order to obtain Upscaling trend lines of different parameters and finally an Upscaling model is created. This model is used to calculate future upscaled wind turbines from the trend lines. The model has some inputs, such as the rotor diameter, wind speed and air density, and it gives as outputs other characteristics of the wind turbine, such as the expected rated power output, the weight and the dimension of different parts.

Keywords: Wind Turbine, Wind turbine database, Upscaling, Upscaling trends, Upscaling modelling

# Preface

This master thesis project is performed at the department of Applied Mechanics, Division of Dynamics, at Chalmers University of Technology (Gothenburg, Sweden). The supervisors of this project are Professor Viktor Berbyuk and Assistant Professor Håkan Johansson. The examiner is Professor Viktor Berbyuk.
This project has been done in connection to the Research Programme of the Swedish Wind Power Technology Center (http://www.chalmers.se/ee/swptc-en). The department of Applied Mechanics is one of the major cooperative partners of the SWPTC.

# Acknowledgements

I would like to thank my supervisors Professor Viktor Berbyuk and Assistant Professor Håkan Johansson, first for offering me the opportunity to perform this project and second, for their time devoted to this project, guidance, support, comments and wise remarks.

I am also very thankful to Professor Enrico Filippi and Pierre Dehombreux, from the Faculty of Engineering of the University of Mons, for giving me the opportunity to perform my Master thesis abroad.
I also want to thank all the people I met in the department of Applied Mechanics at Chalmers for the great talks during our "fika" breaks. Special thanks to Geoffrey, Ana, Stephen, Adrian, Simon and Alexander.
Last but not the least, my most heartfelt thanks go to my parents who have supported me to complete my university studies and without them I would not be the person I am now.

Juan Pablo Sánchez de Lara García.
Götegorg, Sweden, 2013.

# Nomenclature

$\rho_{air}$: Air density.

$E_{air}$: Energy of the wind.

$K_{air}$: Kinetic energy of the wind.

$S$: Swept area.

$d$: Rotor diameter.

$v$: Wind speed.

$m$: Mass of the air.

$W_{nominal}$: Power available from the wind (Nominal power).

$v_{nominal}$: Nominal speed of the wind.

$\eta$: Nominal efficiency.

$V_{ref}$: Reference wind speed average over 10 min.

$V_{av}$: Annual average wind speed.

$I_{ref}(i)$: Turbulence intensity at 15 m/s for the turbulence category i.

## List of symbols

WT: Wind turbine.

DTS: Drive train system.

DD: Direct drive.

GDTS: Geared drive train system.

DDTS: Direct drive train system.

HDTS: Hybrid drive train system.

DDWT: Direct drive wind turbine.

DFIG: Doubly fed induction generator.

SCIG: Squirrel cage induction generator.

PMG: Permanent magnet generator.

EEG: Electrically excited generator.

All WT: means that all turbines are considered, without making any classification.

Existing WT: means that only wind turbines actually in the market are considered.

Geared WT: means that only wind turbines with a geared drive train system and actually in the market are considered.

Direct WT: means that only wind turbines with a direct drive train system and actually in the market are considered.

Hybrid WT: means that only wind turbines with a hybrid drive train system are considered.

Geared WT with prototypes: the same as Geared WT but including the prototypes.

Direct WT with prototypes: the same as Direct WT but including the prototypes.

# Contents

# 1 Introduction

In the last years, the global warming, oil price and nuclear power have been in the spotlight due to their scarcity and the negative environmental impact they generate, like the emission of $CO_2$. Also the increase of the needed electrical power year by year has led the humans to sought the use of new ways to produce energy in a proficient and environmentally friendly way. This was found in the exploitation of renewable energy resources; they contaminate less and do not involve the exhaustion of the energy source.
The Wind energy is one of those renewable energies. The most important environmental benefit of electricity generation by wind power is that it does not produce hazardous wastes, like carbon dioxide emissions to the atmosphere, while during operation.

According to the European Commission, the wind power could be capable of contributing up to 20% of EU electricity by 2020 and as much as 33% by 2030, and it would require to reach 265 GW of wind power capacity by 2020 and 400 GW by 2030 [1].

The UpWind EU research project has set the barriers for a further increase of wind turbine size up to 20 MW. These wind turbines will have a rotor diameter of about 250 m that will be suspended at a height of more than 150 m [1]. Initially, the theoretical implications of Upscaling to such sizes on the weight and loads of the wind turbines have been examined, showing that unfavourable increases in weight and load will have to be addressed.
The Upwind project just investigated the limits of Upscaling with the current technology, without making an investigation about the optimal wind turbine size.
Wind turbines with a rated power of more than 6 MW are now being designed and installed, mostly for offshore operation, and prototypes up to 15 MW are starting to be studied and developed. These new designs will be installed offshore where the wind is not blocked by trees, mountains or other obstacles and has a more constant speed.
The main reason of the Upscaling is the scale economy, larger machines are usually able to deliver electricity at a lower cost than smaller machines, the reason being that the cost of foundations, road building, electrical grid connection, plus a number of components in the turbine (the electronic control system etc.), are somewhat independent of the size of the machine [1]. But the increase in the size of rotors is not only due to scale economy; other factors, such as improvement in design, use of advanced materials (like composite materials), improvement of control systems and also environmental aspects related to administrative limitation on the number of wind turbines in a WT farm, drive the increase in the individual power of each WT for a maximum energy output.

## 1.1 Thesis background

The main work done in the area of wind turbine Upscaling has been done by the European wind energy association (EWEA) in the UpWind project, performed between March 2006 and February 2011. Upwind is one of the largest European R&D wind energy project. This project aimed to develop and verify substantially improved models of the principal wind turbine components for the design and manufacture of very large wind turbines; they will be mainly installed offshore. The wind turbines needed will be very large (more than 8-10 MW) and the rotor diameter will be over 120 m, they set the limit to a rotor diameter of 250 m.[1]

Two papers related to the “Wind turbine Upscaling” topic had been published in the last years (G.Sieros et al[2], J.Helsen et al[3]). The first one (submitted the 2nd of July 2010 and published in 2012) made an analysis of the impact in the cost by Upscaling. First, G.Sieros et al had made a theoretical Upscaling, to determine the characteristics of large WT based on standard, self-similar geometric Upscaling, assuming geometric and aerodynamic similarity. For G.Sieros et al the weight and power were the main criteria and he scales those characteristics by $m \sim s^3$ and $P \sim s^2$, where $s$ is the scale factor. G.Sieros et al calculated the rotor diameter and the hub height of WT with power outputs between 5 and 20 MW. For example for them a WT with a power output of 20 MW will have a rotor diameter of 252 m and a hub height of 153 m. G.Sieros et al also calculated the scaling laws of different loads, such as the aerodynamic forces and moments. Then G.Sieros et al make the same study but considering a real Upscaling, studying the industrial trends. The disadvantage of this study is the diversity of wind turbine designs and external design conditions, but the major advantage is that the data is totally “real world”. G.Sieros et al used the rotor diameter as scale factor and he calculated the design extreme loads, the nacelle mass and the blade mass as a function of the rotor diameter. For them the nacelle mass scale as $s^2$ and the blade mass as $s^{2.5}$. Finally with these two studies G.Sieros et al calculated the cost benefits of upscaled turbines and the optimum size configuration for very large wind turbines. G.Sieros et al concluded that without technology improvements, the Upscaling results in an unfavourable weight and cost increase.

The second paper published about “Wind turbine Upscaling”, written by J.Helsen et al([3]), gives an overview of the different trends of the loads and vibrations in the gearbox under Upscaling conditions. This study was limited to the increasing of the flexibility of different gearbox structural components, the influence of different gearbox suspension on the isolation of non-symmetrical loads and the influence of the gearbox mounting on the potential turbine structural excitation. It was concluded that the Upscaling increases significantly the rotor forces and the structural flexibility.

## 1.2 Thesis objective

The objective of this thesis is to study existing concepts of drive train system (DTS) of wind turbines (WT), in particular with respect to how Upscaling has been done for WTs with existing concepts of DTS. To perform this study, a database containing all different kinds of WTs is created and then analysed to obtain trend lines for different characteristics of the WTs. Then a model has been created to calculate those different characteristics of the WTs for future upscaled wind turbines, based on the database.

## 1.3 Thesis overview

- Chapter 2 State of the art of Wind Turbines: presents a description of WTs, their different elements, types of drive train system and generators.
- Chapter 3 Wind Turbine Upscaling: Creation of a database of the main characteristics of different WTs designs and analysis of it to obtain Upscaling trends.
- Chapter 4 Upscaling model: describes and gives a tool to calculate the main characteristics of WT based on the database trend lines.
- Chapter 5 Conclusion: gives a resume of the project and gather the most important points of the project and propose the area where the study of the Upscaling should continue.
- Appendix A includes less important trend lines and fit parameters of all the trend lines included in the report.
- Appendix B includes a description the model and how to use it.
- Appendix C includes a tutorial about how to use the Upscaling model.

# 2 State of the art of Wind Turbines

Wind turbines had been used for thousands of years, the earliest machines were called windmills and were used to pump water and grind grain. Actual Wind turbines appeared in the 80s due to the oil crisis of the 70s. Let's start with the definition of a wind turbine: a wind turbine is a machine that converts wind energy to electricity. The kinetic energy of the wind is first transformed to mechanical energy by means of the rotation of the blades, and then this mechanical energy is transformed in electrical energy by a generator, that it is connected to the grid.

There are mainly two types of wind turbines regarding the axis of blade rotation: they are named horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) (Figure 2.1). The VAWT are like an "eggbeater". The horizontal axis wind turbine is the most used technology; there is a high level of maturity reached by the top producers of Wind Turbines (Siemens and Vestas for example). In this work only the horizontal axis wind turbine will be studied, from this point when mentioning wind turbine refers to HAWT. The most common configuration of HAWT is a rotor with two or three blades rotating at a low speed.

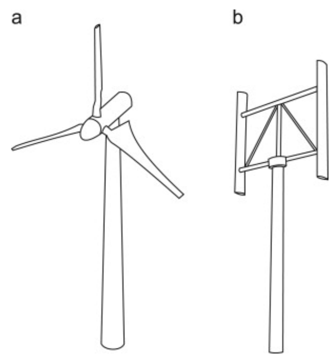



Figure 2.1: *HAWT (a) and VAWT (b) [4]*

## 2.1 Different part of a Wind Turbine

A wind turbine is composed by different elements, the main elements are listed in the Figure 2.2 and described in the following list:

- Foundation (1): Transfers the vertical and horizontal loads to the ground; the configuration changes if the WT is placed onshore or offshore.
- Grid connection (2): In order to reduce electric losses, a transformer converts the medium voltage from the wind turbine generator to high voltage. The WT is not always connected to the grid, the WT is connected once the generator reaches the synchronous speed, in other words, when the generator matches the grid frequency.

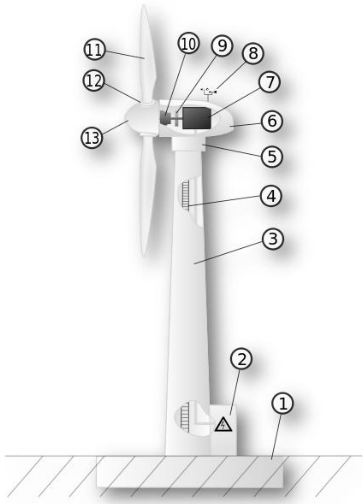



Figure 2.2: *Illustration of the main parts of a wind turbine [5]*

- Tower (3): Usually manufactured from steel or concrete. It consists of different sections bolted to each other. The tower has a ladder (4) inside or a lift to permit service and maintenance access to the top of the WT.

- Yaw control (5): Controls the turbine direction to always be on the direction of the wind.

- Nacelle (6): The housing of all the elements of the upper part of the WT. The main role of the nacelle is to protect the internal components of the WT against the environment. The nacelle is connected to the tower by the yaw assembly. There are heaters/coolers fans inside the nacelle to control the temperature. To facilitate the access of operators to bigger WT, the nacelle may include a helicopter-platform.

- Generator (7): The part of the WT that transform the mechanical energy to electrical energy. It is placed at the top of the tower, inside the nacelle.

- Anemometer (8): To measure the wind speed, used for control systems.

- Mechanical brake (9): part of the drive train system.

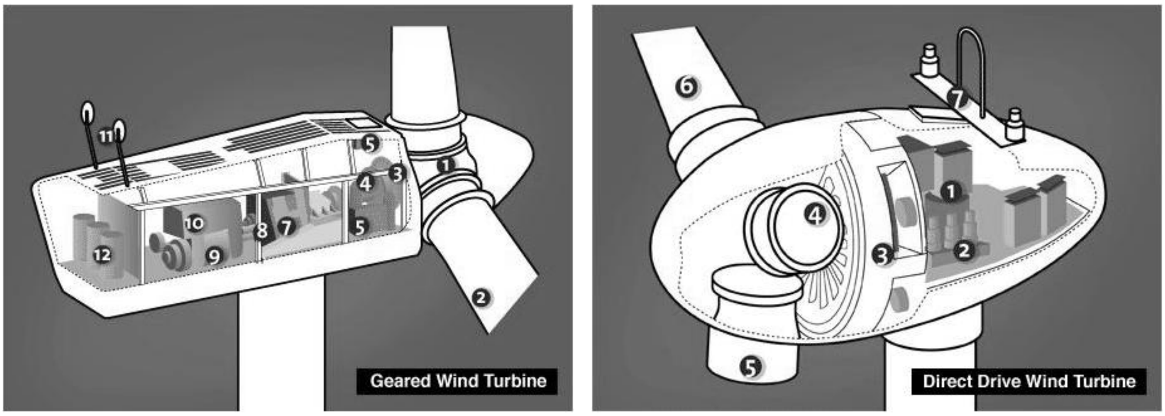
- Drive train system (10): it is the part that transfers the energy from the rotor to the generator. There are mainly three types of drive train system: geared, direct-drive and hybrid. A more detailed description of these types of drive system will be presented in the next section (2.2).

- Blade (11): The part of the WT that converts the wind kinetic energy to a rotation of the rotor hub.

- Rotor hub (13): it connects the blades to the main shaft. It also contains the mechanism to control the pitch of the blades (12). The blade pitch control turns the blades to change the angle of attack with the goal of changing the rotation speed of the rotor.

## 2.2 Drive train system

As mentioned before the drive train system (DTS) is the part of a WT that transfers the energy from the rotor to the generator. There are two main configurations of DTS: indirect drive train system (also called Gearbox DTS) and direct drive train system (also known as gearless DTS). A third one, call hybrid DTS, exist; it is a mix between the geared and direct DTS. The drive train system is considered the critical part of a WT in terms of reliability as its downtime per failure is higher than other components [6]. Inside the DTS, the gearbox is the main cause of these failures and high downtime.




(a) *Geared WT* (b) *Direct drive WT*

Figure 2.3: *Drive train systems [7]*

### 2.2.1 Geared DTS

The vast majority of wind turbines currently installed use some type of geared concept. The gearbox is used to increase the rotation speed of the generator to match the frequency of the grid (50 Hz in Europe). A synchronous generator with two, four or six poles would require a rotation speed between 1000 and 3000 rpm. If the gearbox is not used, a 43 m diameter rotor connected to a 6 poles asynchronous generator (in a 50 Hz grid) needs to rotate at a rotational speed of 1000 rpm, at this rotational speed the tip of the blade has a speed of:

$$v = w\ [rad/s]\ \frac{rotor\ diameter/2}{pairs\ of\ poles}\ [m] = 1000\frac{2\pi}{60}\frac{43/2}{3} = 739.644m/s. \tag{2.1}$$

This value is higher than twice the sound speed, which is impossible.

The main problem encountered in this system is the reliability. This is principally due to the misalignment in the drive train system. The misalignment is considered as one of the main contribution to the failure of the DTS. The misalignment is a condition where the centerlines of coupled shafts do not coincide. It is a deviation of relative shaft position from a collinear axis of rotation. It generates vibrations that reduce the service life and availability of gears. There are two types of misalignment: parallel and angular. In the real world a mix of these two types is found.

The main compounds of a geared drive train system are: the hub, main bearing, main shaft, gearbox, brake, high speed shaft, generator and bedplate (Figure 2.4).

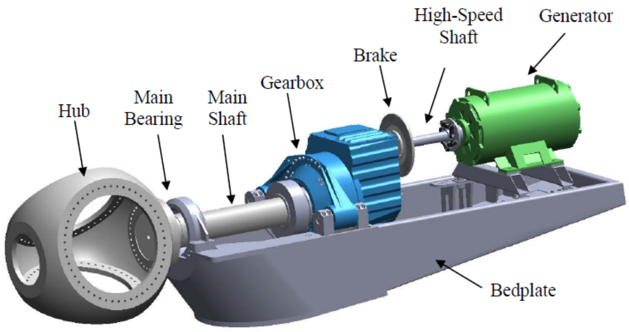



Figure 2.4: *Compounds of a geared DTS [8]*

There are different configurations for the gearbox, but the most common features two first planetary stages followed by a parallel stage, as represented in the Figure 2.5.

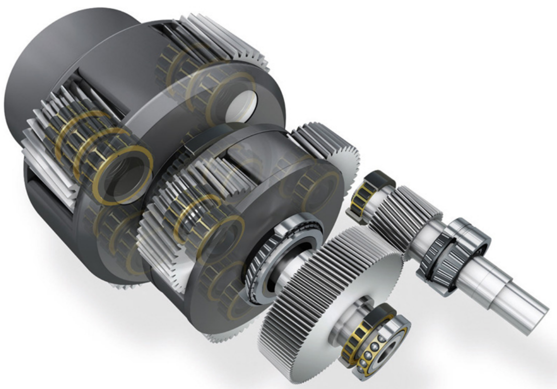


Figure 2.5: *Common gearbox in WTs [9]*

### 2.2.2 Direct DTS

Using a direct DTS instead of a geared DTS simplifies the drive train system because the rotor hub and the generator are directly interconnected to form one gearless unit. As there are fewer rotating components, the mechanical stress is reduced and the equipment's technical service life, reliability and efficiency are increased. Also wind turbine maintenance and service costs are reduced due to its fewer wearing parts and no need to change the gear oil [10]. But not all are advantages, at the actual stage this technology is far from being cost-efficiency as the geared DTS technology [11].

Although it seems that things are simplified by the side of the transmission, it is not the case at the stage where the mechanical energy is transformed in electrical energy: the generator. The same type of generators used for the geared DTS cannot be used for the DDTS, because the rotational speed in DDTS is much lower than in GDTS. Generators with a higher number of poles are needed, in order to match the grid frequency. The generator shaft rotational speed, function of the number of poles (n) and the grid frequency (f), is given by the following formula:

$$w_{generator}[rpm] = 120\frac{f[Hz]}{n} \tag{2.2}$$

So if we increase the number of poles, the rotational speed needed by the generator is as well reduced. For example if we have a rotor speed of 20rpm directly connected to the shaft of the generator (gear ratio equal to 0), we will need a generator with 300 poles for a 50 $Hz$ grid.
The main compounds of a direct drive train system are: the rotor hub, main shaft, main bearing and the generator. An example of a DDTS configuration is shown in the precedent Figure 2.3b.

### 2.2.3 Hybrid DTS

Hybrid DTSs are a mix between geared and direct DTSs. Hybrid DTS has a number of gearbox stages between 1 and 2. The aim of this technology is to have a gearbox as simple as possible with a generator of a size near the ones used for the geared DTS. There is also another type of DTS that is considered a hybrid, it consists on the use of multiple generators, an example is the WT design manufactured by Clipper (Figure 2.6). This type of DTS results in a more compact of the arrangement between the gearbox and the generator than in the other DTS configurations.

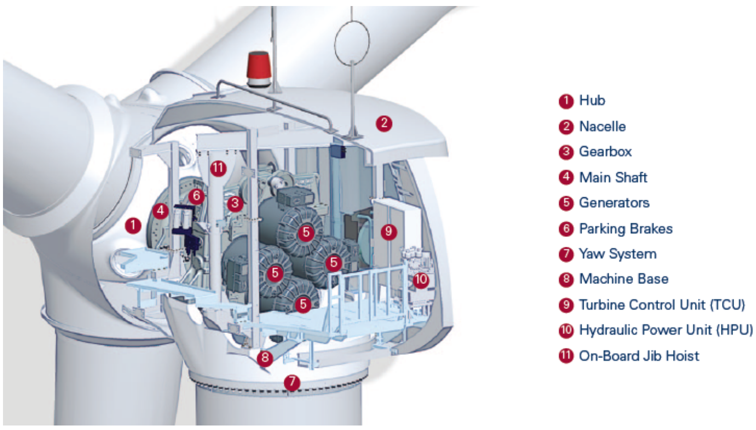
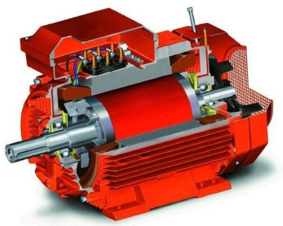



Figure 2.6: *Hybrid DTS with multiple generators [12]*

## 2.3 Types of generator

Wind turbines can use asynchronous and synchronous generators, the choice depend of the type of DTS used. For the asynchronous generators there are mainly two types: Squirrel cage induction generators (SQIG; Figure 2.7a) and doubly fed induction generators (DFIG; Figure 2.8a). These machines are simple, reliable, inexpensive and well developed. The asynchronous generators are directly connected with the electricity grid [13].

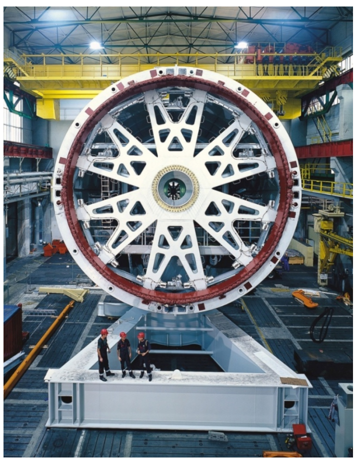


(a) *Squirrel cage induction generators [14]*

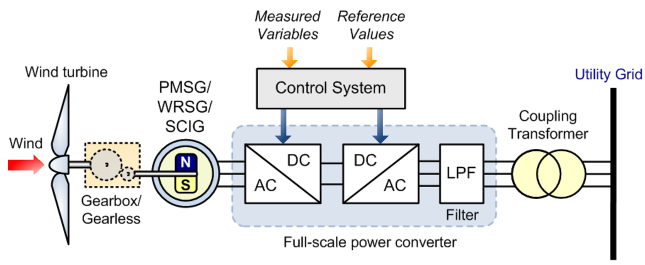
(b) *Doubly fed induction generator [15]*

Figure 2.7: *Asynchronous generators*

On the other hand, the two main types of synchronous are: Permanent magnet generators (PMG) and electrically excited synchronous generators (EESG), respectively. PMG are the synchronous generator that is the most used. In a permanent magnet generator (PMG) the excitation field is provided by a permanent magnet instead of a coil. As the wind speeds is not constant, the PMG cannot generate electrical power with a fixed frequency. They are connected to the grid through an AC-DC-AC converter (Figure 2.8b). PMG are widely used for direct drive application. The generator should have large pole numbers and are physically large than a similarly rated geared machine as it can be seen in Figure 2.8a. Synchronous generators applied to DD systems, in comparison with induction machines, are heavier and more expensive and are still in development [13]. Figure 2.9 shows a resume of the main types of generators used for WT application.



(a) *Permanent magnet generator [10]*




(b) *Power converter of a PMG [16]*

Figure 2.8: *Synchronous generators*

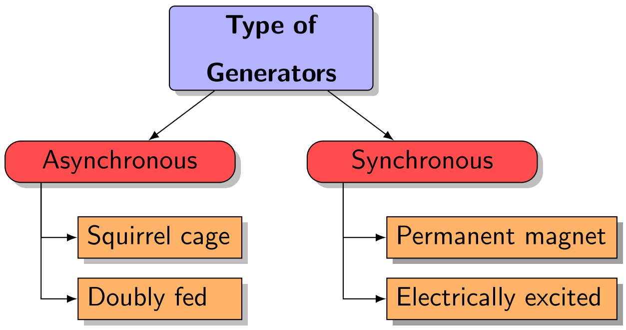



Figure 2.9: *Main types of generators used in WTs*

## 2.4 Trade-off of the types of DTS

As a resume Figure 2.10 shows the 3 types of DTS and the type of generator they use:

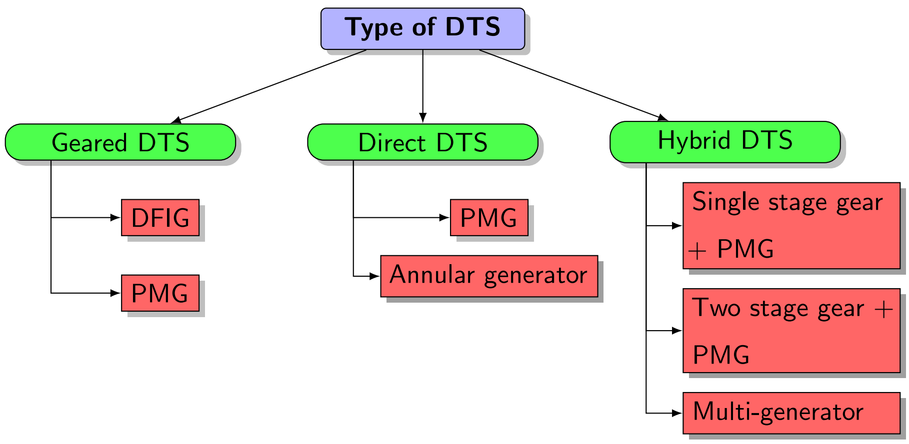



Figure 2.10: *DTS resume*

Figure 2.11 shows a comparison of the weight of the gearbox and generator for the geared, direct and hybrid DTS configurations. The level 3 means heavy, 2 medium, 1 light and 0 null.

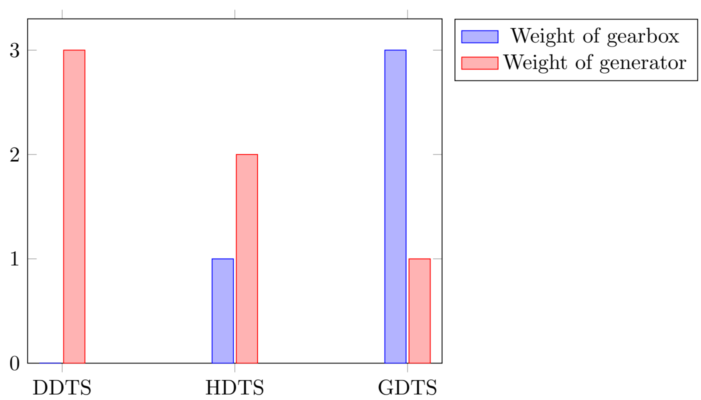



Figure 2.11: *Trade-off of the DTS configurations*

# 3 Wind Turbine Upscaling

This section is dedicated to the study of the Upscaling of WT. This is performed by creating a database of a large number of WT models and analysing it. All the information of each WT model is obtained by the brochures of the manufacturer or/and by contacting the manufacturer. As not all the manufacturers have the same confidentiality policies for some WT models the information needed was obtained and for others it was not possible. If sometime in the future it is possible to obtain the missing data, the database could be updated.

## 3.1 Database

The database is created in an Excel file and comprises 238 different wind turbine designs from 35 manufacturers. The data collected for these different designs is: the rated power, the rotor diameter, the swept area, the rotor speed (minimum and maximum), the blade length, the root and tip chord, the tip speed, the type of drive train system, the number of stages in the DTS, the transmission ratio, the tower height, the weight of the rotor, blades, nacelle, tower and at the top of the tower, the cut-in/nominal/cut-out wind speed, the nominal power wind, the nominal efficiency, the type of the generator, the voltage, the frequency, on/off-shore, the wind turbine class (wind and turbulence class) and if the WT is in the market or if it is a prototype. All these parameters are described in the next section.

## 3.2 Definition of the parameters included in the database

Before taking a look into the database, the parameters including in it must be defined in order to fully understand what is being studied. The parameters included in the database are the following:

- **Rotor diameter:** see Figure 3.1.
- **Rotor swept area:** The area swept by the blades (Figure 3.1).
- **Rated power:** It is the maximum power output that the wind turbine can achieve called rated power which is lower than the power available in the wind. The rated power is used to rate the WT, all WT manufacturer rate their wind turbines by the rated power. If the wind speed becomes higher than the nominal speed the pitch control of the blade limit the rotation speed of the blades and therefore the output power at its maximum level, this can be seen in the Figure 3.2.
- **Minimum rotor speed:** The rotational speed of the rotor for which the generator start producing electrical power.
- **Maximum rotor speed:** The rotational speed of the rotor for which the generator produce its maximum output electrical power.

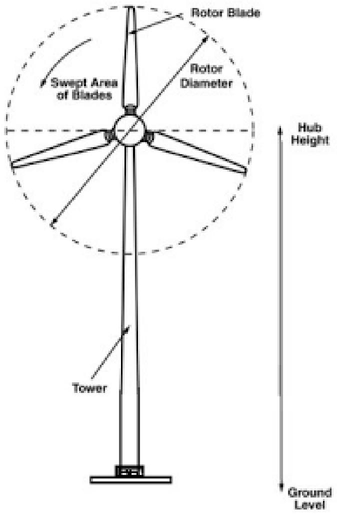



Figure 3.1: *Rotor diameter, swept area and hub height [17]*

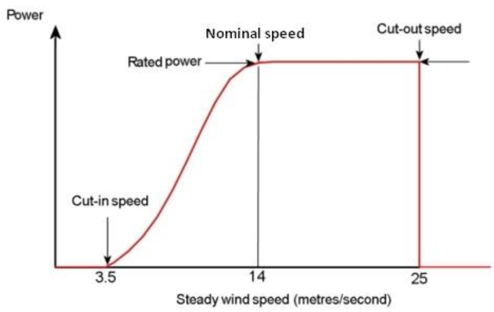



Figure 3.2: *Typical wind turbine power output with steady wind speed [18]*

- **Blade length:** The distance between the section C-C and B-B in the Figure 3.3.

- **Blade tip chord:** Section B-B in the Figure 3.3.

- **Blade root chord:** The bigger chord of the blade, section A-A in the Figure 3.3.

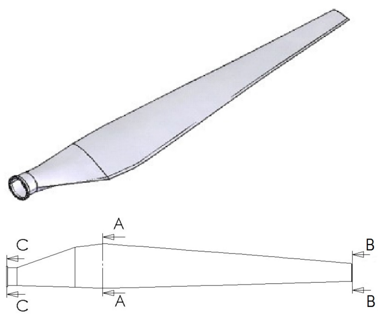



Figure 3.3: *Root and tip chord*

- **Tip speed:** The tip speed is an important parameter regarding the acoustic noise generated by the WT. There are restrictions about the acoustic noise of WT in zones near population or protected areas. But offshore those restrictions are not applied which is an advantage for the offshore market because as the tip speed increase the torque decrease, which allow to reduce the mass and cost of some elements in the DTS.

- **Geared DTS:** A DTS that comprise at least 3 gearbox stages. A full description of a geared DTS is found in the section 2.2.1. In the database a "TRUE" value in this parameter means that a geared DTS is used.

- **Direct DTS:** A DTS that does not comprise any gearbox stage in the DTS. A full description of a DDTS is found in the section 2.2.2. In the database a "TRUE" value in this parameter means that a DDTS is used.

- **Hybrid DTS:** A DTS that comprise between 1 and 2 gearbox stages. A full description of a hybrid DTS is found in the section 2.2.3. In the database a "TRUE" value in this parameter means that a hybrid DTS is used.

- **Tower height:** The distance between the ground level and the hub height in the Figure 3.1.

- **Blade mass:** The mass of one single blade.

- **Rotor mass:** The mass of the 3 blades and the hub.

- **Nacelle mass:** The mass of the whole housing plus all the components inside it (generator, gearbox, bearings) without including the rotor mass.

- **Top mass:** The total mass at the top of the tower, it is the sum of the weight of the rotor and the nacelle.

- **Tower mass:** The mass of all the segments of the tower.

- **Cut-in wind speed:** The lowest wind speed for which the blades start to rotate and electrical energy is produced. As it can be seen in the database, the value of this speed is between 2 and 5 $m/s$, this value does not change because there is no point on trying to produce energy at low wind speed (Figure 3.2).

- **Nominal wind speed:** The wind speed for which the maximum output power (rated power) is achieved (Figure 3.2).

- **Cut-out wind speed:** The wind speed for which the WT stops producing electrical energy. As the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and is usually around 25 metres per second (Figure 3.2).

- **Nominal power:** Is the power generated from the wind energy. It is also defined as the rate of wind energy that passes through an area per unit of time: $W_{nominal} = E_{wind}/t$ [19]. If we consider that the wind energy is given by the kinetic energy of the wind ($K_{wind}$), the nominal power is obtained as follows:

$$E_{wind} = K_{wind} = \frac{1}{2}mv^2 \tag{3.1}$$

where m is the mass of air and v is the wind speed [19]. The mass (m) is given by the following formula:

$$m = \rho_{air} \cdot S \cdot v \cdot t \tag{3.2}$$

Where $\rho_{air}$ is the density of air (considered equal to 1.225 $kg/m^3$), $v$ is the wind speed, $t$ is the considered period of time and $S$ is the area for which the wind passes through, called swept area. The swept area is calculated by:

$$S = \frac{1}{4}\pi \cdot d^2 \tag{3.3}$$

Where $d$ is the rotor diameter of the WT.[19]
And finally, from the kinetic energy and the mass of air equations, the power available from the wind (nominal power) is:

$$W_{nominal} = \frac{1}{2} \cdot m \cdot \frac{v^2}{t} = \frac{1}{8} \cdot \rho \cdot \pi \cdot d^2 \cdot v^3_{nominal} \tag{3.4}$$

- **Nominal efficiency:** The efficiency, $\eta$, also called the power coefficient of the wind turbine, is simply as the maximum power delivered by the WT divided by the power available from the wind:

$$\eta = \frac{rated\ power}{nominal\ power} \tag{3.5}$$

The nominal efficiency tells how efficiently a turbine converts the energy in the wind to electricity. It has a theoretical limit of 59,3%, called the Betz limit [20].

- **Generator type:** Defines the type of generator used by the WT. The two most popular generators are the double fed induction generator and the permanent magnet generator.

- **Voltage:** It is the output voltage of the generator to the grid. The most common value is 690 V.

- **Frequency:** The electrical frequency of the grid. WTs are most of the time designed to match the two types of electric frequencies (50 and 60 Hz).

- **Onshore:** Installation of the WT in land. In the database, a "TRUE" value in this parameter means that the WT is designed to be installed onshore.

- **Offshore:** Installation of the WT in the sea. In the database, a "TRUE" value in this parameter means that the WT is designed to be installed offshore, a "False" value means the opposite. Some WT can be installed onshore and offshore.

- **WT class**: Represents the site where the WT will be placed. Wind turbine classes are defined in terms of wind speed and turbulence parameters. The wind turbine classification offers a range of robustness clearly defined in terms of the wind speed and turbulence parameters. There are 4 wind speed classes and 3 turbulence classes. Wind speed classes I, II and III do not cover offshore conditions, for such sites a class S is defined, the parameters of this class are defined by the designer. Table 3.1 gives the wind speed and turbulence parameters for the different WT classes.

Table 3.1: Wind speed and turbulence parameters [21]

| **Wind turbine class** | I | II | III | S |
|---|---|---|---|---|
| $V_{ref}$ | 50 | 42,5 | 37,5 | Values specified by the designer |
| $V_{av}$ | 10 | 8,5 | 7,5 | |
| $I_{ref}(A)$ | | 0,16 | | |
| $I_{ref}(B)$ | | 0,14 | | |
| $I_{ref}(C)$ | | 0,12 | | |

$V_{ref}$ is the reference wind speed average over 10 min.

$V_{av}$ is the annual average wind speed at the site.

$I_{ref}(i)$ is the expected value of the turbulence intensity at 15 m/s for the turbulence category i.

A designates the category for higher turbulence characteristics.

B designates the category for medium turbulence characteristics.

C designates the category for lower turbulence characteristics.

## 3.3 Analysis of the data

The aim of the database is to obtain the trend lines of the most important parameters. The data is imported to Matlab and analysed with the "Curve Fit" toolbox. During this analysis a difference between the different kind wind turbines is performed, in other words, the wind turbines will be classified in 5 different groups: WT prototypes and WT in the market (called All WT), just the wind turbines that are in the market (called Existing WT), WTs with a geared drive train system (called Geared WT), WTs with a direct drive train system (called Direct WT) and, finally, WTs with an hybrid drive train system (Hybrid WT excel file). For the three groups taking into account the type of DTS, a subgroup where the WT under development are included is also created.

For the entire trend lines calculated the fit parameters and the goodness of the fit is included in the appendix B. Also as some statistical parameters are used in order to evaluate the fits, a description of these parameters is included in the appendix A.

### 3.3.1 Rated power

One of the first things to analyse is the relation between rated power and the rotor diameter, larger rotors means more power captured from the wind, but it also means more cost to build it and an increase in the top mass. The Figures 3.4 and 3.5 show the evolution of the rated power with respect of the rotor diameter considering (3.4) or not (3.5) the prototypes. Figure 3.5 shows that the bigger WT uses an hybrid DTS followed by DDTS; geared DTS predominate for the power range between 1 and 4 MW, this range has been the main focus of the Wind Industry for the last decade. If the prototypes are now considered (Figure 3.4) it can be seen that the tendency is to use Direct DTS for bigger WT, the hybrid DTS is also present for bigger WT but in a smaller number than DDTS.

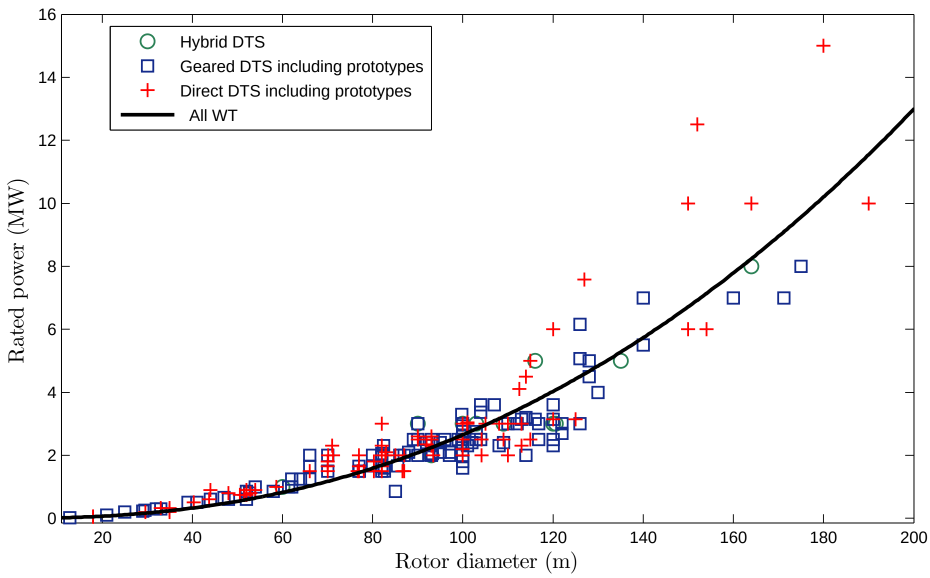



Figure 3.4: *Evolution of the rated power with respect of the rotor diameter: all WT*

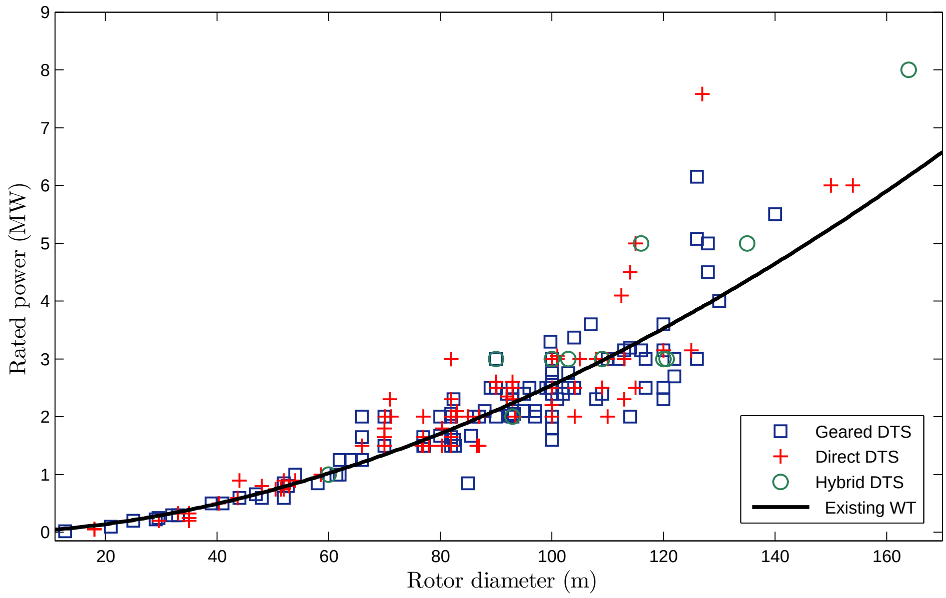



Figure 3.5: *Evolution of the rated power with respect of the rotor diameter: existing WT*

Figure 3.6 compare the evolution of the trends considering first all the existing designs and then considering all wind turbine prototypes:

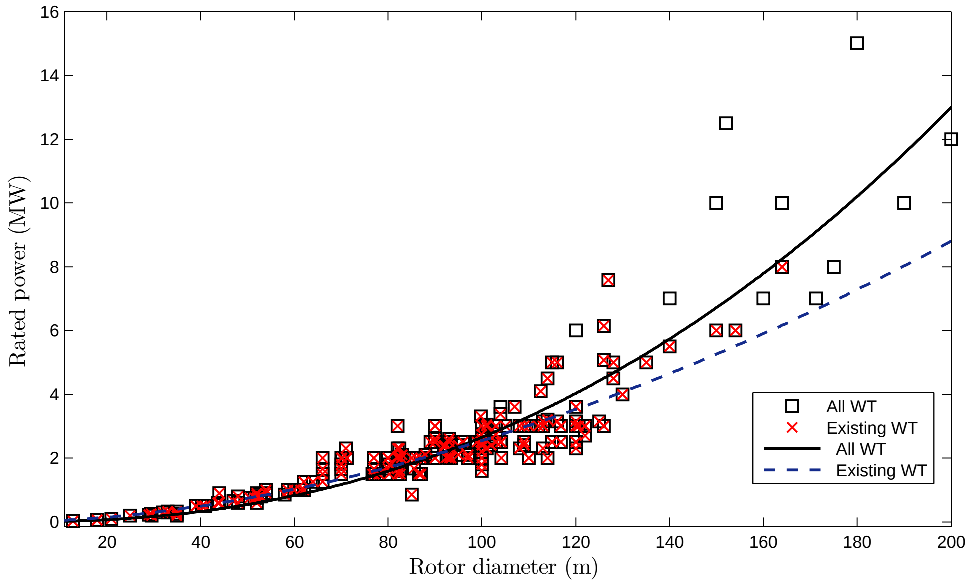



Figure 3.6: *Evolution of the rated power with respect of the rotor diameter: real and prototypes WTs*

As we can see, from Figure 3.6, there is a difference between the two trends, this can be explained by the fact that maybe manufacturer were a little bit too confident with their prototypes assigning a higher rated power to it. The trend line for "All WT" follows a power law with an exponent of 2.292, while for the "Existing

WT" this exponent is 1.789. The details of the curve fitting can be found in the appendix B.1.1.

In the following Figure we can see the evolution the rated power with respect of the rotor diameter for the 3 different types of DTSs:

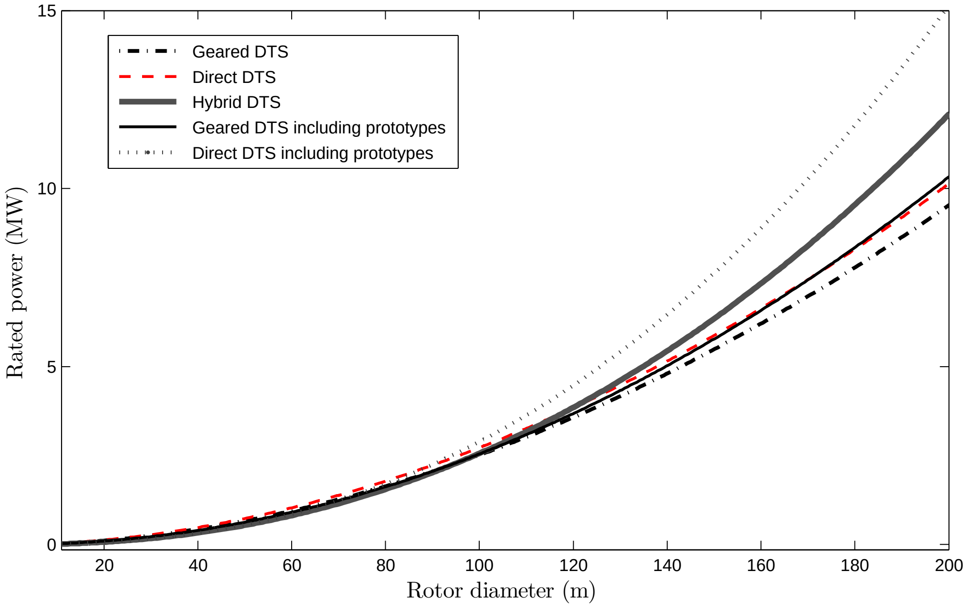



Figure 3.7: *Evolution of the rated power with respect of the rotor diameter: Different DTS*

As already put in evidence in the last comparison, trend lines that include prototypes tend to raise faster that without including the prototypes. A conclusion that can be made from Figure 3.7 is that for the same size of rotor diameter, DDTS seems to give a rated power slightly higher than geared DTS at the moment and for future WT this difference increase. This means that DDTS are more efficient than geared DTS, surely because of improvement in the design of generator and the disappearance of the gearbox, which avoids power losses caused by the gearbox.

### 3.3.2 Blade length

As it can be seen in the Figure 3.8, the evolution of the blade length is linear with respect of the rotor diameter. We can observe a point that is out of the trend line, this point correspond to a prototype made by the Norwegian company Sway Turbine, called ST10. Sway Turbine creates a WT which have a generator directly driven by the rotor; each blade is mounted to a blade support that straddles the generator. That is why even if they have blades of 67m it has a rotor diameter of 164 m. This "anomaly" is not taken into account to calculate the trend line because it does not correspond to the standard design of WTs.

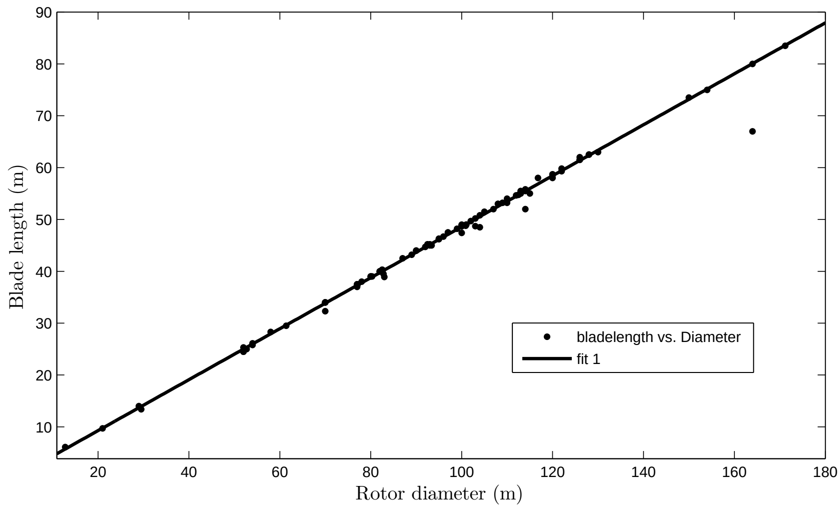



Figure 3.8: *Evolution of the blade length with respect of the rotor diameter*

### 3.3.3 Tower height

The reason why the tower height increase is logically due to the increase of the diameter but there is another point to consider: the site where the WT will be placed, this means that a same WT model can have different tower heights. As there is no reason why the tower height could be influenced by the type of DTS, only the global trend is studied (Figure 3.9).

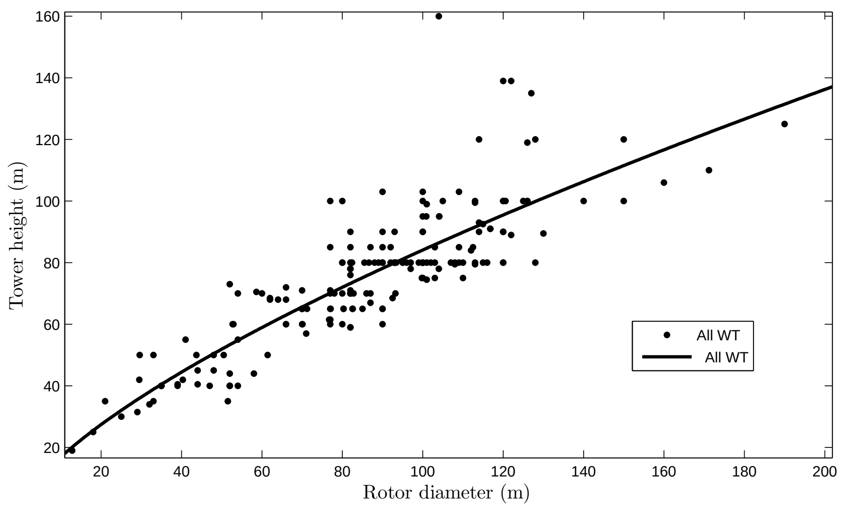



Figure 3.9: *Evolution of the tower height with respect of the rotor diameter*

As we can see, the different types of DTS are spread around the trend line. The most common tower height is around 80 m, for WT with a rotor diameter between 80 and 130 m.

### 3.3.4 WT weight

Another important parameter in the design of WTs is the weight of the different elements of the WT. More weight means more transportation cost, more cost and difficulties on raising the elements at the top of the tower and more loads on the bearings, tower and foundations. In this work, only the weight of the blades, rotor, nacelle and the top mass (weight at the top of the tower) is covered.

#### Blade mass

Bigger rotor means bigger blades, in the section 3.3.2 the trend line of the size of the blades was found; here the correlation between the mass of the blades and other parameters, such the diameter and the rated power, is studied. As there is no data for the prototypes and the Hybrid DTS, we will only focus on the global trend line and the trend line of geared and direct DTS.

Let's start with the evolution of the blade mass with respect of the rotor diameter, first taking a look at the global evolution (Figure 3.10) of the blade mass.

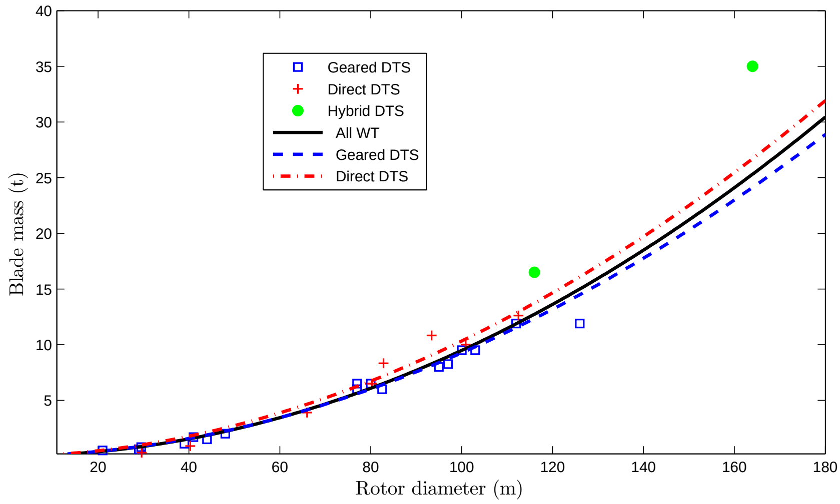



Figure 3.10: *Evolution of the blade mass with respect of the rotor diameter*

As we can see from the Figure 3.10 the blades of a WT with a direct DTS seem to be heavier than the ones with a geared DTS. In a DD wind turbine there is an increase of the torque [22]; to deal with this increase in the torque, the stiffness of the blade must be increased which leads to an increase in the weight of the blades.

If we compare the blade mass with the blade length, we can expect to obtain the same result as comparing it with the diameter the Figure can be found in the appendix B.1.4.

Comparing the blade mass with the rated power (Figure 3.11), it shows that in principle the geared WTs are heavier than the DD, this is contradictory to the results obtained previously but it can be explained by the fact that for the same rated power, as it has been seen in the section 3.3.1, a DDTS have a smaller rotor than a geared DTS.

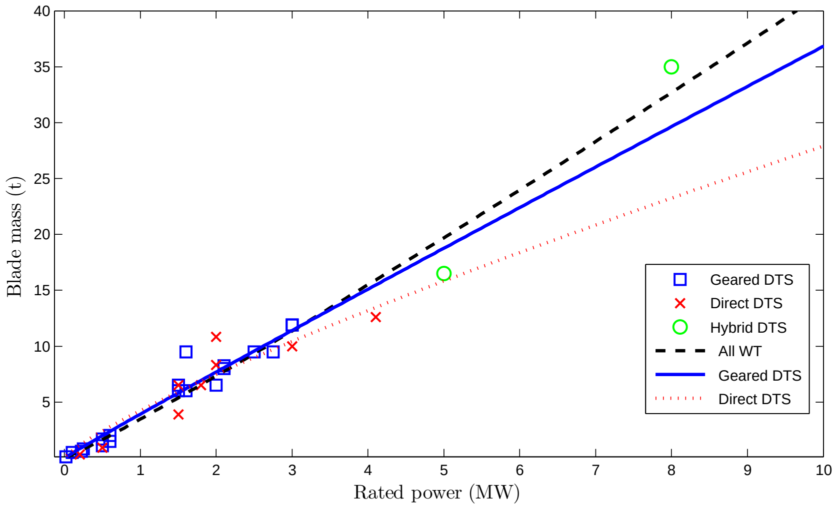



Figure 3.11: *Evolution of the blade mass with respect of the rated power: types of DTS*

### Rotor mass

As the rotor mass include the mass of the 3 blades and the hub, we can expect the same type of evolution as for one single blade (section 3.30). Only global, geared DTS and direct DTS trend lines are studied because of the lack of data for the Hybrid DTS and prototypes.

The Figure 3.12 compare the rotor mass with respect of the rotor diameter, showing the trend lines for the two types of DTS and the global trend. As for the blades, larger DDTS rotors are heavier than geared DTS rotors.

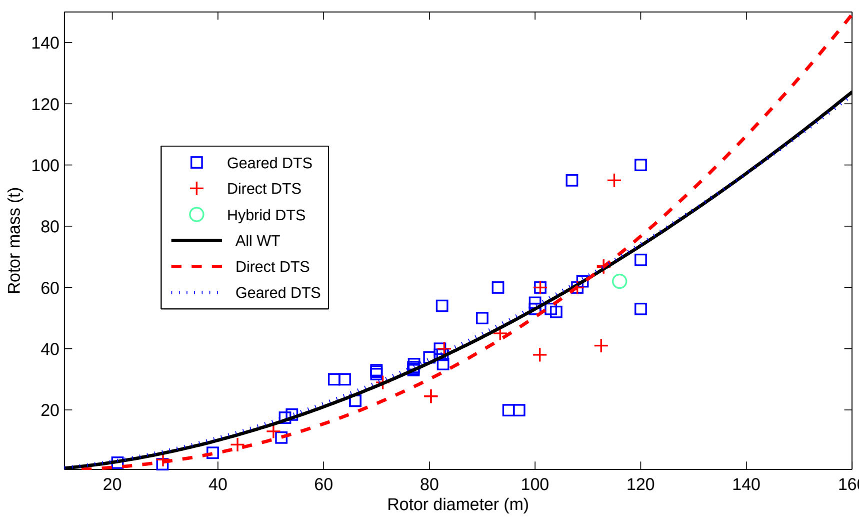



Figure 3.12: *Evolution of the rotor mass with respect of the rotor diameter*

### Nacelle mass

As well as for the precedent studies only global, geared DTS and direct DTS trend lines are studied.
Figure 3.13 shows that DDTS are heavier than Geared DTS, comparing it with the rated power (the Figure can be found in the appendix B.2.2) the same thing is observed. The nacelle mass does not include the mass of the rotor, so the only reason why DDTS are heavier is that the generator of a DDTS is heavier than the gearbox and the generator of a geared DTS. The direct drive generators are bigger than the ones used for a geared DTS, this is due to the fact that DD generators need more poles and this increase the generator diameter. Another reason why the DD generator are heavier is that due to that high torque the mechanical construction must be very rigid. Also as the DD generator are bigger, they need also a big housing, it leads to bigger sizes of the nacelle, which increase also the weight for the DDTS nacelle.

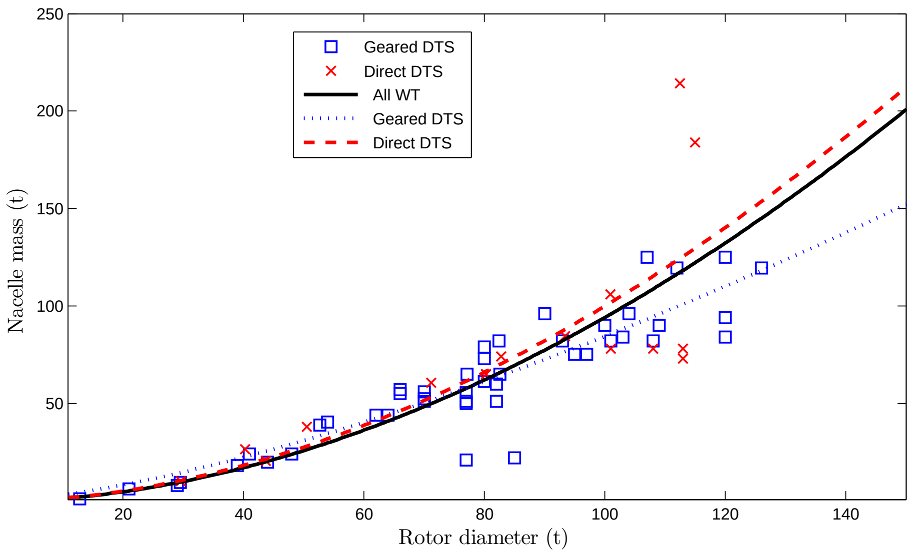



Figure 3.13: *Evolution of the Nacelle mass with respect of the rotor diameter*

### Top mass

As well as for the precedent studies only global, geared DTS and direct DTS trend lines are studied.
We have seen that the blades and the nacelle of DDTS WTs seems to be heavier than geared WTs, this is also verified if we compare the top mass with the rotor diameter. Figure 3.14 shows the evolution of the top mass considering all types of DTS. If we compare the top mass with the rated power (Figure 3.15), we can observe that the relation between this two parameters is close to be linear, this can be verified taking a look on the parameters of the trend lines (appendix B.2.3).
As this is the last study concerning the weight of WTs, it can be concluded that DDTS are heavier than geared DTS, due to the size of the generator used but they seems to be more efficiency regarding the size of the rotor and the rated power.

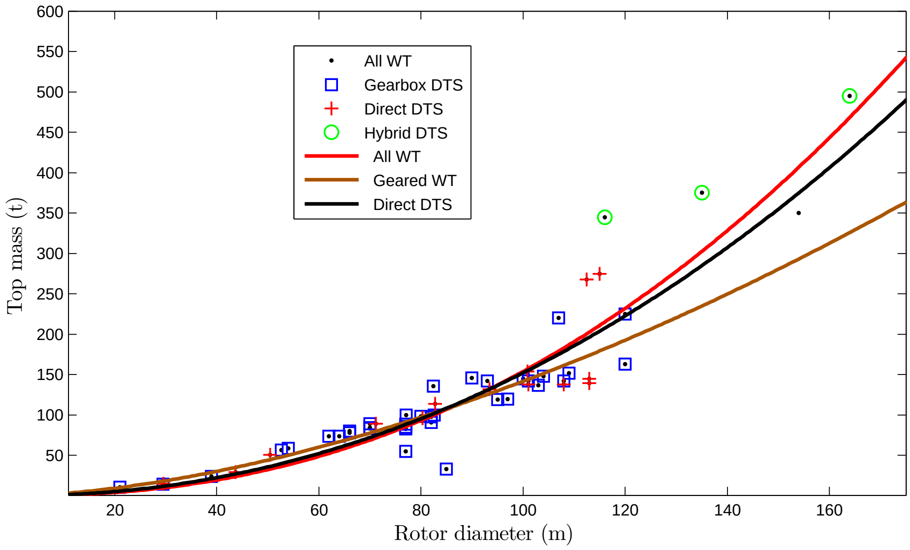



Figure 3.14: *Evolution of the Top mass with respect of the rotor diameter*

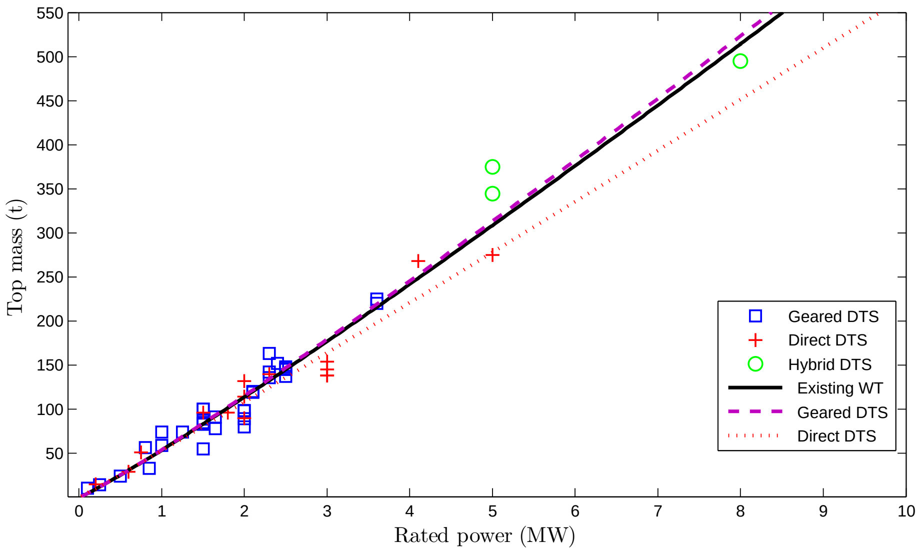



Figure 3.15: *Evolution of the Top mass with respect of the rated power*

### 3.3.5 Root and tip chord

Let's compare now the evolution of the other two parameters considered in the design of the rotor blades: the root and the tip chord.

Comparing the root chord with the blade length (Figure 3.16), one can see that the root chord increase with the size of the blade diameter, which is logical because larger blades need to be much thicker in order to withstand stresses. As the blade length is related to the rotor diameter, the same kind of trend is obtained (Figure B.1 in the appendix B.1.8).

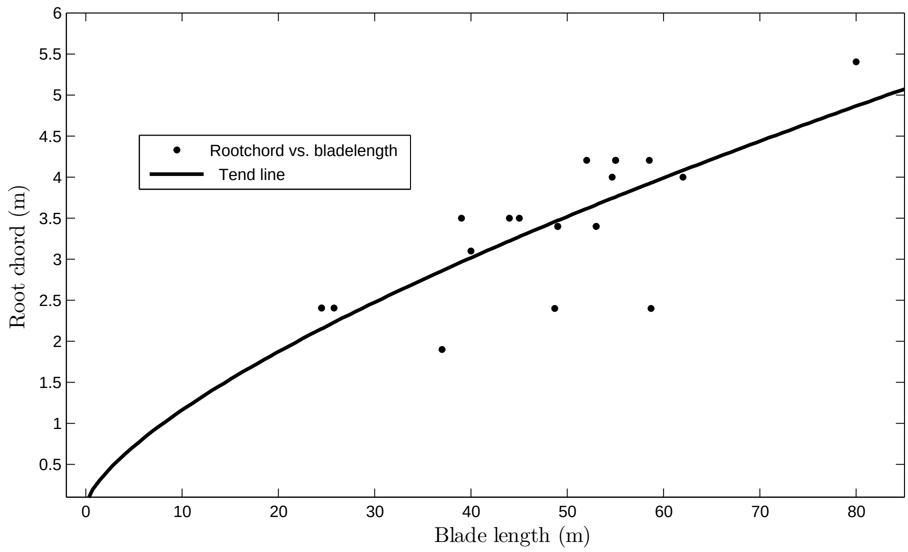



Figure 3.16: *Evolution of the root chord with respect of the blade length*

Now, let's see what happens if we compare the root chord and the tip chord in Figure 3.17. Logically, if the root chord raise the tip chord will do it too.

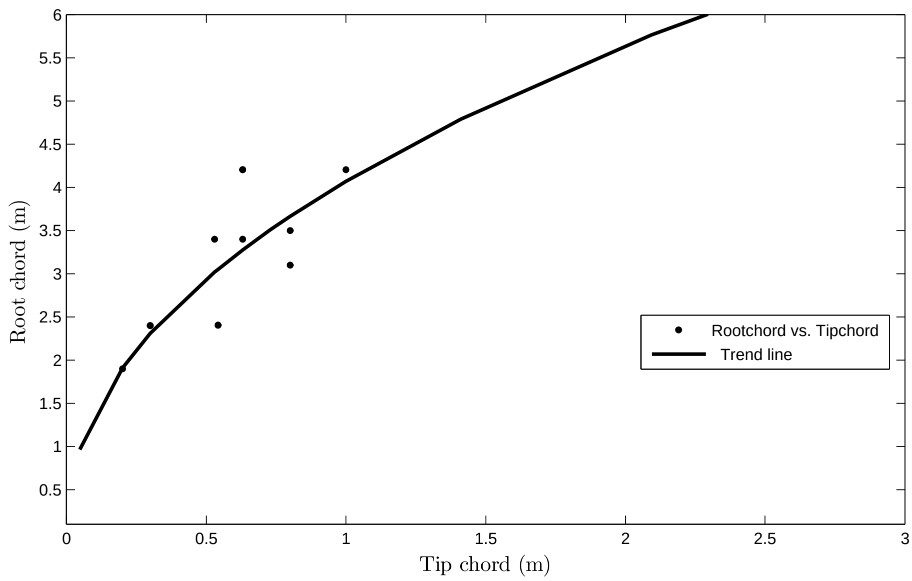



Figure 3.17: *Evolution of the root chord with respect of the tip chord*

### 3.3.6 Rotor speed

Let's take a look now on evolution of the two rotor speeds. The more important one is the maximum rotor speed because is the speed for which the WT will generate its maximum power output (the rated power), while the minimum rotor speed is the speed for which the WT starts generating power.

#### Maximum rotor speed

The first comparison, as for the other studies, is related to the evolution of the rotational speed within the increase of the rotor diameter. The Figure 3.18 shows this evolution considering all types of WT.

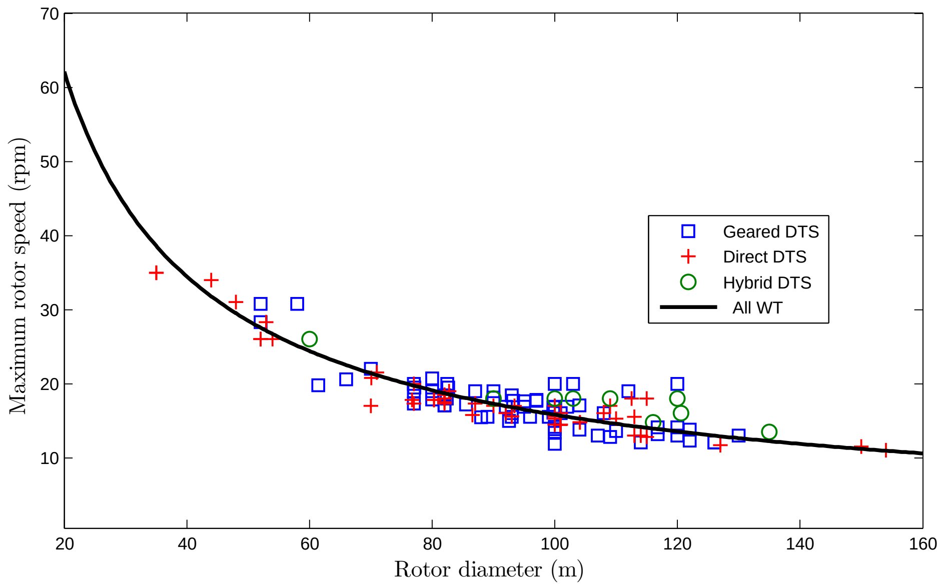



Figure 3.18: *Evolution of the maximum rotor speed with respect of the diameter: All WTs*

As we can see from Figure 3.18, the curve follows very well the evolution of the points and the different types of DTS seems to stack in the same area, this can be verified taking a look on the trend line of the different DTS in the Figure 3.19.

One could also think that as for different WT classes we have different wind speed, the rotor speed could vary between different WT classes, but comparing the evolution for each class (Figure 3.20) we can observe that this assumption is not true and the different trend lines are close between each other.

If we compare now the evolution of the maximum rotor speed within the rated power (Figure 3.21), we obtain the same conclusion as for the comparison with rotor diameter.

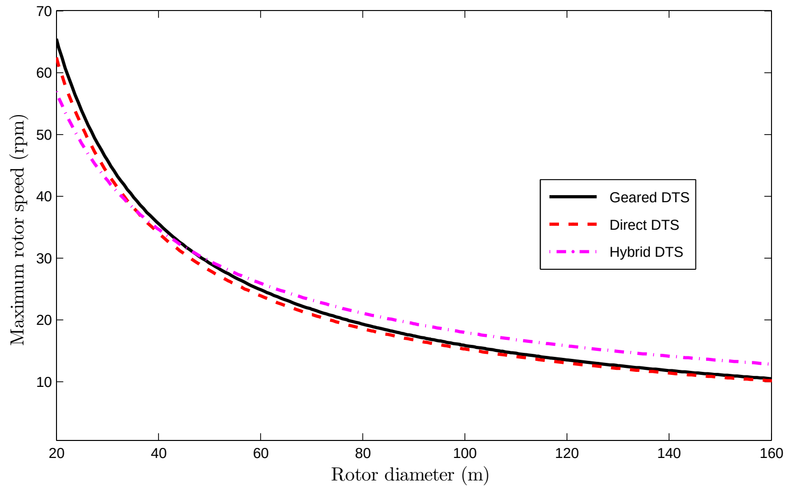



Figure 3.19: *Evolution of the maximum rotor speed with respect of the diameter: types of DTS*

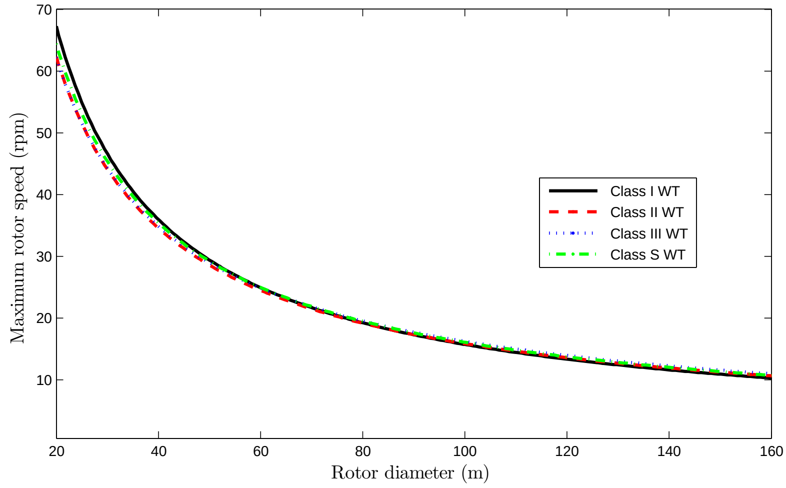



Figure 3.20: *Evolution of the maximum rotor speed with respect of the diameter: WT classes*

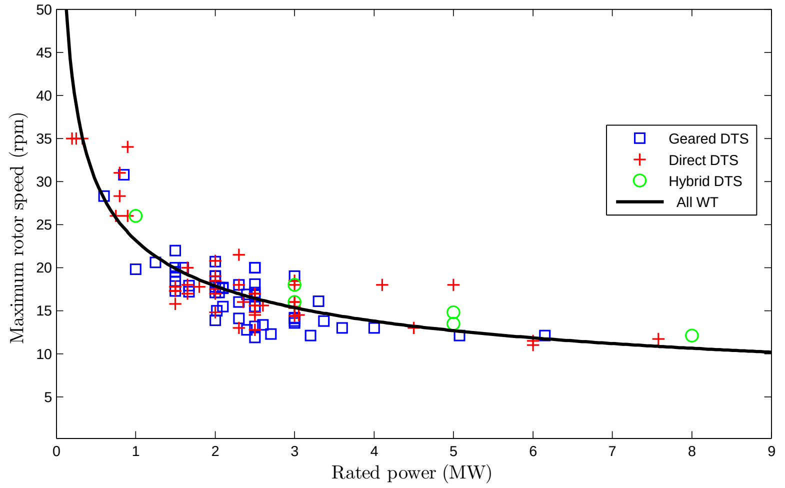



Figure 3.21: *Evolution of the maximum rotor speed with respect of the rated power*

### Minimal rotor speed

As this parameter is less important than the maximal rotor speed, only its evolution with respect of the rotor diameter is performed.

As well as for the maximum speed there is no difference between WT classes (Figure 3.22) but if we make the difference between DTS types (Figure 3.23) we observe that there is a difference between geared and direct DTS. This is due to the type of generator used by geared and direct DTSs. DDTS use Permanent magnet generators with a large number of poles, by controlling the number of poles that are switch on, the frequency can be matched with the grid frequency for lower rotor speed and then start producing energy at lower rotor speed than the GDTS. The global trend line can be found in the appendix B.1.10, Figure B.2.

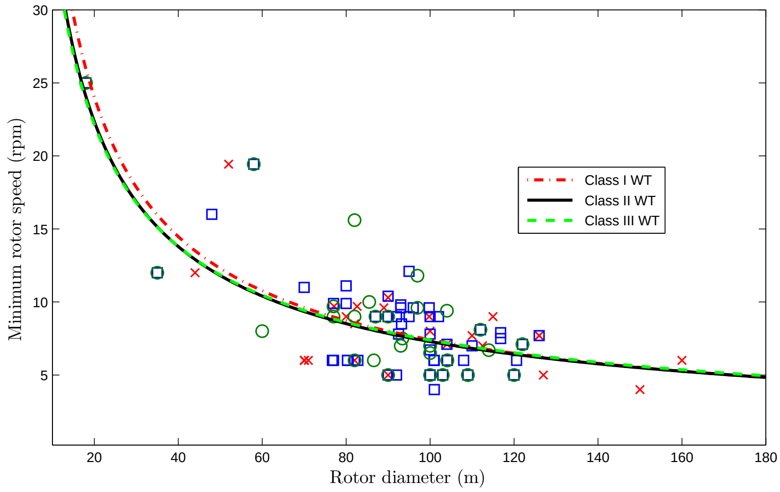



Figure 3.22: *Evolution of the minimum rotor speed with respect of the diameter: WT classes*

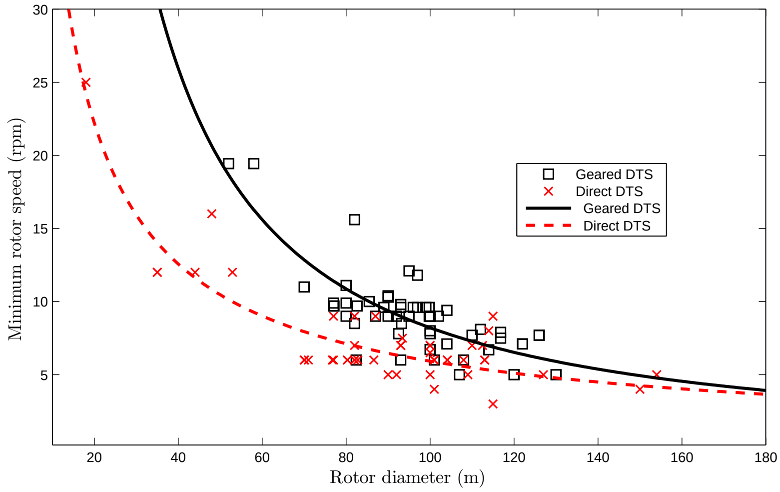



Figure 3.23: *Evolution of the minimum rotor speed with respect of the diameter: types of DTS*

### 3.3.7 Tip speed

The tip speed is proportional to the rotor diameter, so for a fixed rotor speed, if the rotor diameter increases the tip speed will also increase. But we have seen that when the rotor diameter increases, the rotor speed decreases. Figure 3.24 how the tip speed evolve while the rotor diameter increases. The tip speed does not vary too much when increasing the rotor diameter. There are some noise environmental restrictions that limit the tip speed because at high tip speed the WT generate more noise.

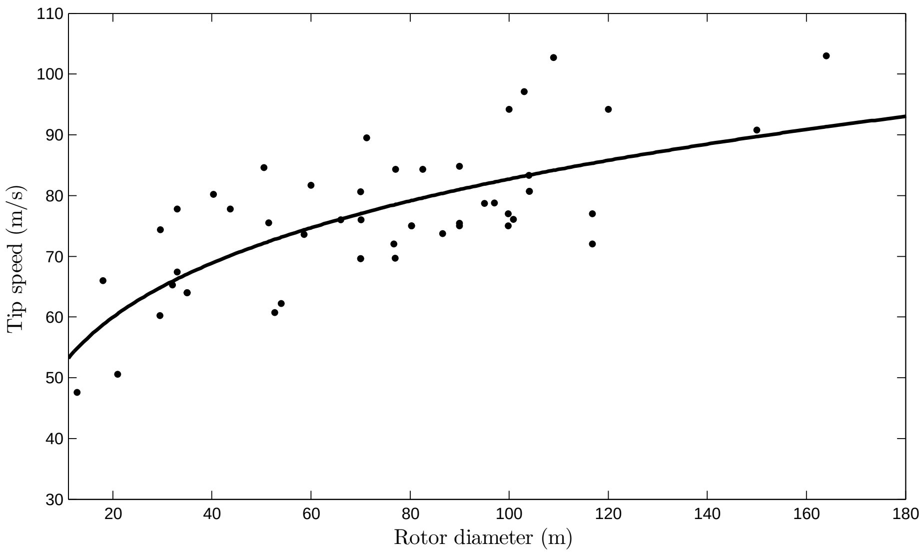



Figure 3.24: *Evolution of the tip speed with respect of the rotor diameter*

### 3.3.8 Wind speed

There is no need to draw some graphs to analyse the cut-in, nominal and cut-out wind speed, a quick look in the database allows one to see that those parameters are more or less the same for all the different WT designs. The only parameters that varies more is the nominal speed because it depend on the design of the wind turbine, as a reminder the nominal wind speed is the wind speed for which the WT generates its maximum power output. In the Table 3.2 we can find the lowest, average and maximum value of the parameters.

Table 3.2: Cut-in, nominal and cut-out wind speed

| **Wind speed** | **Minimum** | **Average** | **Maximum** |
|---|---|---|---|
| Cut-in | 2 | 3.16 | 5 |
| Nominal | 9.1 | 12.47 | 17 |
| Cut-out | 19 | 24.64 | 34 |

### 3.3.9 Nominal power

As a reminder, the nominal power is given by: $W_{nominal} = \frac{1}{8}\rho \cdot \pi \cdot d^2 \cdot v_{nominal}^3$. So, we already know how the nominal power grows with the increase of the rotor diameter for a fixed nominal wind speed. The Figures 3.25 and 3.26 shows the evolution of the nominal power with respect of the rotor diameter for all values of the nominal wind speed.

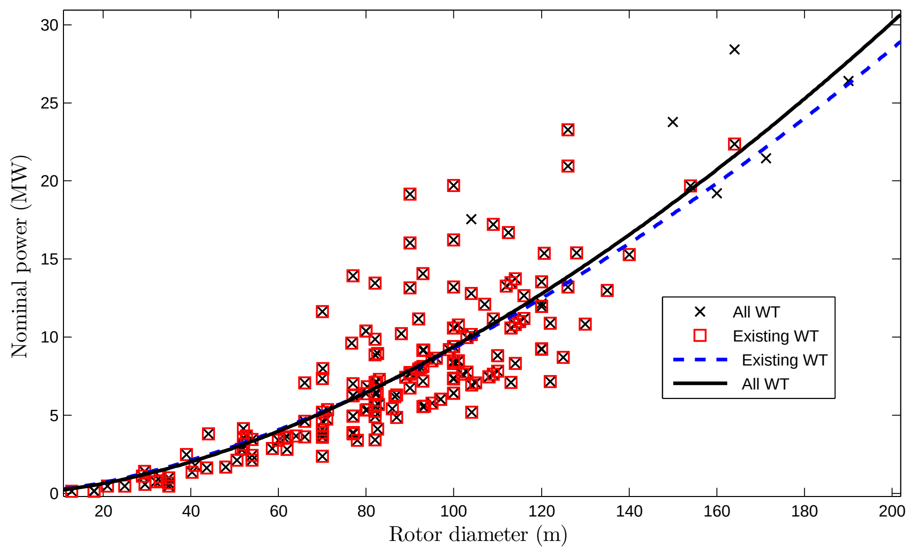



Figure 3.25: *Evolution of the Nominal power with respect of the rotor diameter*

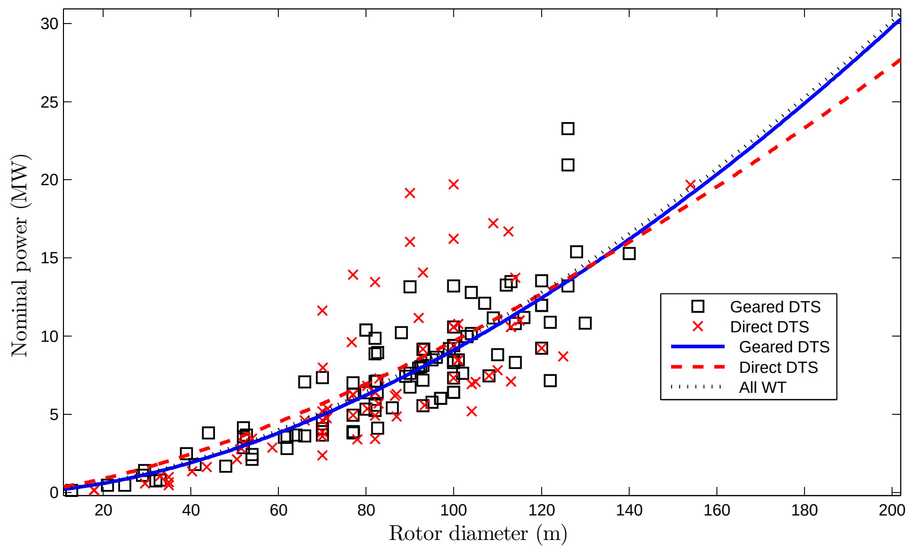



Figure 3.26: *Evolution of the Nominal power with respect of the rotor diameter: different DTS*

### 3.3.10 Nominal efficiency

The nominal efficiency is an important parameter to analyse because it gives a first overview of the WT performance. Let's see if a trend can be found, first the nominal efficiency is compared against the rotor diameter (Figure 3.27), then against the rated power (Figure 3.28) and finally against the nominal power (Figure 3.29).

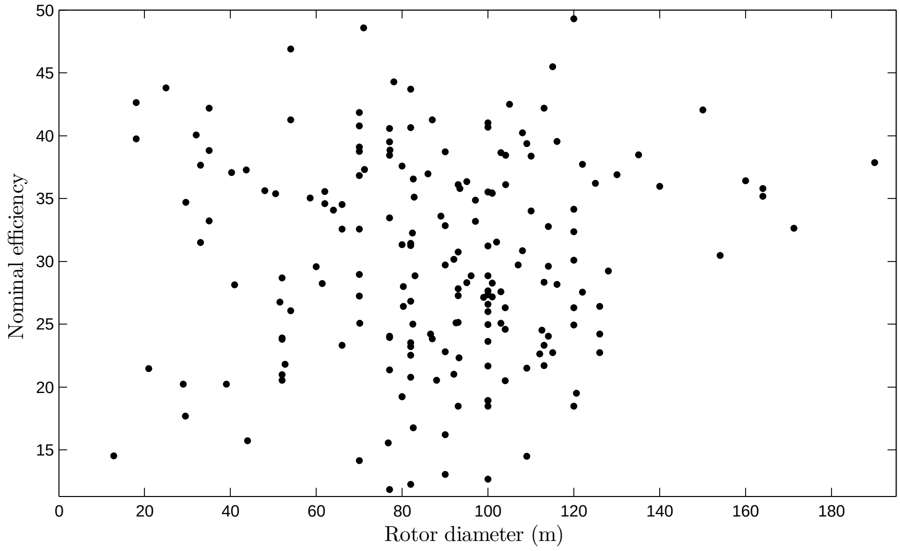



Figure 3.27: *Evolution of the Nominal efficiency with respect of the rotor diameter*

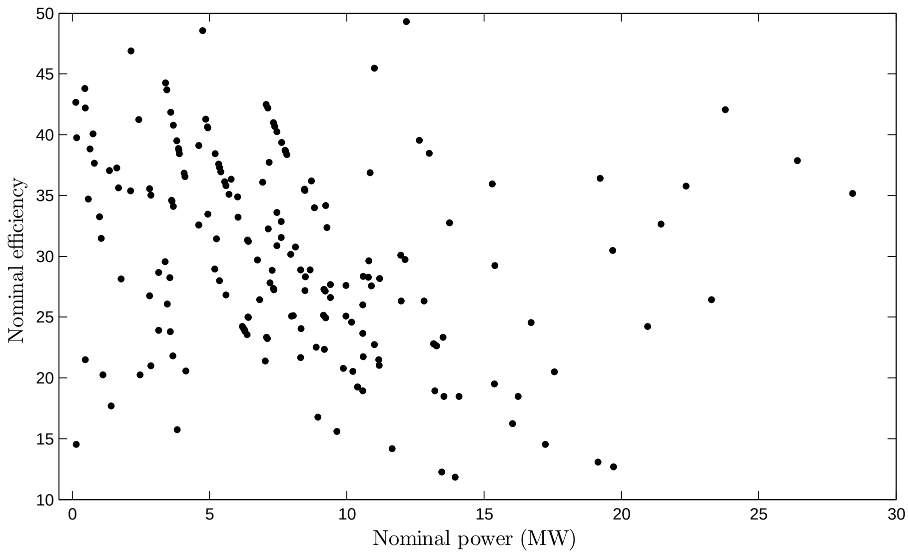



Figure 3.29: *Evolution of the Nominal efficiency with respect of the nominal power*

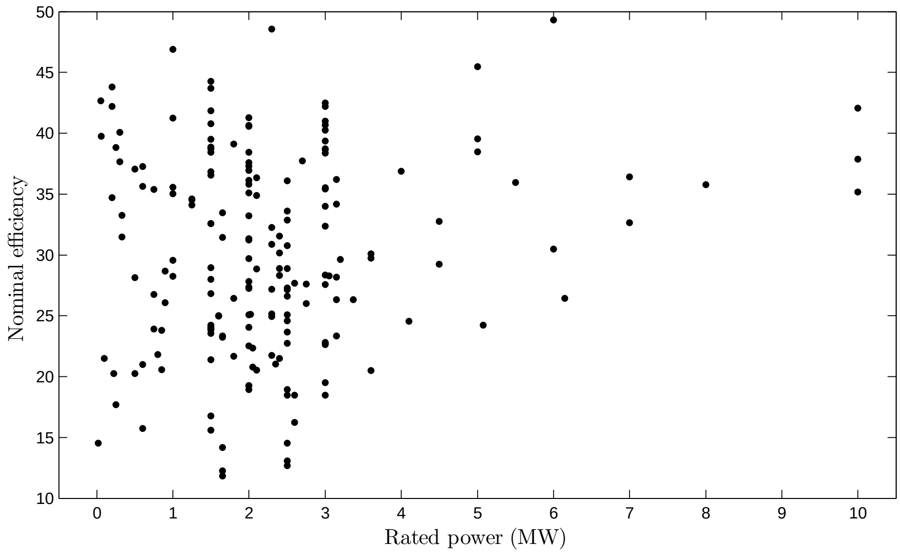



Figure 3.28: *Evolution of the Nominal efficiency with respect of the rated power*

As we can see in these three Figures (3.27, 3.28 and 3.29), the nominal efficiency seems not be directly correlated to one of these 3 parameters.

### 3.3.11 Type of Generator

The two types of generator that are most used at the moment are the "double feed" and the permanent magnet. The trends show that in the near future more and more WT with DDTS are designed, which means that PM generators will be highly demanded. But they are heavier and more expensive than the DFIG; this is due to the use of rare earth mats and the need of a more robust mechanical structure to face the high torque produce by the low speed of the generator rotor.

These disadvantages lead some companies to develop new types of generator for WT applications. A technology under development that deserves to be pointed is the High temperature superconductor (HTS) generator by SeaTitan. They claim that using high temperature superconductor, instead of copper, will translate in a much smaller, lighter, efficient and less expensive than conventional WT generators. Wind turbines with this technology will be tested by 2014 or 2015 ([23], [24]).

## 3.4 Discussion/conclusions about WT Upscaling

Different trend lines have been seen; let's now draw some conclusion about future upscaled wind turbines:

- First of all, let's talks about the DTS. As WT manufacturers wants to get rid of the gearbox to increase the reliability and decrease the time under reparation of the DTS, future WTs will have a direct drive train system or a simple gearbox with one stage gear.

- This will lead to the use of synchronous generators, nowadays PMG are widely used but their size, weight and cost will increase significantly with larger WTs. New generators should be developed, in order to be more cost efficiency with respect of conventional generators (DFIG), reduce their size and increase their efficiency. As mention in the precedent section 3.3.11 HTS seems to match those characteristics and companies as SeaTitan and GE Energy are developing such kind of generators.

- Another important problem of WT Upscaling is the transport and assembly of all the parts. For onshore application it will be really difficult to transport big blades, think about a blade of 100 meters or more driven through a common road or villages. Figure 3.30 shows the transport of a blade of 48.5 m length. This problem could be solved by splitting the blade into two or more sections, as it is done for the towers. But not only the size is a problem, also is the weight. Trucks have a load limit, trucks with a larger load capacity will be needed, not just to transport the blade but also for other parts of the WT that will also increase in size and weight. For offshore sites, the transport problems still exist but they are less important as big cargo ships are used. The only problem is to transport the blades and other elements from the workshop to the cargo.

- Concerning the assembly, big cranes with a high load capacity will be required. They will have to lift blades and other elements up to more than 150 meters.

- The top mass must be reduced. If the trend continues and no improvement are achieved in this area, a WT with a rotor diameter of 250 m will have an estimated top mass around 1000 tonnes, the equivalent more than 3 Airbus 380-800 planes, which weight empty of charge and fuel 276,8 tonnes. The main reasons of this weight increase are the rotor and the generator, so the reduction in their weight must be one of the main focuses for the future.

- Another problem is the manufacturing of large blades. As mentioned before, blades of more than 100 meters will be required in the future. Figure 3.31 shows the mould use to manufacture the biggest blade (75 meters).


Figure 3.30: *Transport of a 48.5 m blade [25]*

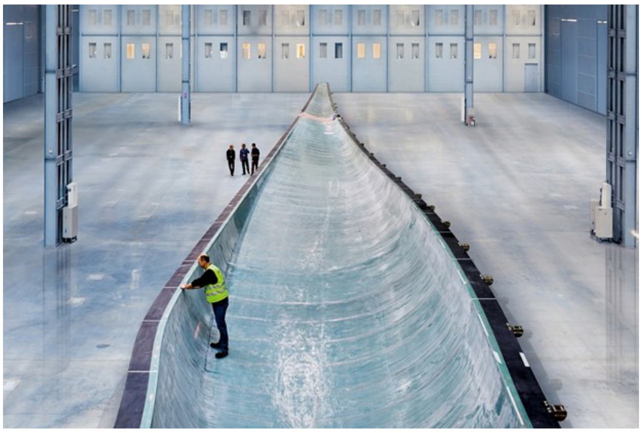


Figure 3.31: *Mould used to manufacture the 75m Siemens blade [26]*

# 4 Upscaling model

Based on the database and the trend lines calculated in the precedent section a model, which calculates the main characteristics of a WT, is created. The model will be mainly used to calculate future upscaled wind turbines. The model used two software: Matlab and Excel. Excel is used to modify or update the database, and then a script in Matlab read the data from the database and calculates the trend lines and the fit parameters of each trend line. The fit parameters are automatically imported by Matlab to another Excel file. This Excel file is where the inputs can be change in order to calculate the characteristics of the desired Upscaled WTs. The Figure 4.1 shows a scheme of how the model works.

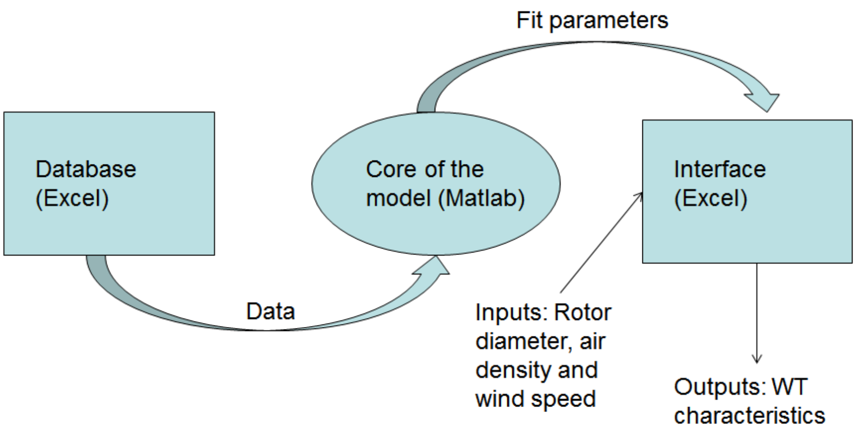



Figure 4.1: *Scheme of the Upscaling model*

The inputs of the model are: the rotor diameter, the wind speed and the air density. The air density is most of the time fixed to 1.225 $kg/m^3$. The characteristics calculated by the model (outputs) are: the rated power, nominal power, nominal efficiency, minimum and maximum rotor speed, blade length, tip and root chord, tip speed, tower height, blade mass, rotor mass, nacelle mass and top mass. A tutorial on how to use the model is located in Appendix C.

As seen in the chapter 3, the characteristics evolve differently while different categories are considered (All WT, Existing WT, Geared DTS, Direct DTS, etc...), different values for the same characteristic will be obtained. The model allows to calculate those characteristics following the different category trend lines: All WT, Existing WT, Geared DTS, Direct DTS, Hybrid DTS, Geared DTS with prototypes and Direct DTS with prototypes.
It should be pointed that, if the users want more accurate values for the Hybrid DTS category, more WT designs should be added to the database, as there are not as much data as for the other categories.

Let's calculate with this model the characteristics of future WT designs with for example a rotor diameter of 175, 200 and 250 m and compare it with two WT designs: The "M5000" manufactured by Areva with a rotor of 135 m and a maximum power output of 5 MW and the 'GE 4.1-113" manufactured by GE Energy with a rotor of 112.5 m and a maximum power output of 4,1 MW. The table 4.1, just below, collects the values of the main characteristics, calculated by the model following the trend lines of the group "All WT", for these 5 WTs (2 existing and 3 upscaled WTs):

Table 4.1: Parameters for upscaled wind turbines with a rotor diameter of 175, 200 and 250 m

| | **GE Energy** | **Areva** | **Upscaled WT 1** | **Upscaled WT 2** | **Upscaled WT 3** |
|---|---|---|---|---|---|
| Rotor diameter (m) | 112.5 | 135 | 175 | 200 | 250 |
| Wind speed (m/s) | 14 | 11.4 | 14 | 14 | 14 |
| Power output (MW) | 4.1 | 5 | 9.48 | 12.82 | 21.21 |
| Nominal power (MW) | 16.7 | 13 | 25.74 | 33.61 | 52.52 |
| Nominal efficiency | 24.54 | 38.46 | 36.48 | 38.13 | 40.39 |
| Min rotor speed (rpm) | 7 | 4.5 | 4.87 | 4.43 | 3.78 |
| Max rotor speed (rpm) | 18 | 13.5 | 9.82 | 8.77 | 7.25 |
| Blade length (m) | 54.75 | - | 85.47 | 97.76 | 122.34 |
| Root chord (m) | - | - | 5.13 | 5.63 | 6.58 |
| Tip speed (m/s) | - | - | 92.51 | 95.01 | 99.35 |
| Tower height (m) | 85 | - | 123.96 | 135.96 | 158.65 |
| Blade mass (t) | 12.614 | 16.5 | 38.83 | 53.91 | 93.27 |
| Rotor mass (t) | 41 | 62 | 145.63 | 185.36 | 277.41 |
| Nacelle mass (t) | 214.324 | 233 | 265.1 | 338.73 | 510.2 |
| Top mass (t) | 293.166 | 344.5 | 529.38 | 707.56 | 1148.96 |
| Tip chord (m) | - | - | 0.98 | 1.08 | 1.27 |

# 5 Conclusion

The main objective of this thesis was to study how wind turbines are growing in size and draw conclusions about what to expect in the future. The study has been done by creating a database with 238 different wind turbine designs from 34 manufacturers from all over the world. Then, by comparing different characteristics of these designs with respect of the main parameters of a wind turbine (such as the rotor diameter and the rated power), trend lines were obtained. For the same comparison, different trend lines were calculated: those trend lines considered the type of drive train system and make the difference if the wind turbine design is a prototype or if it is already in the market. This allows to compare different DTS technologies and concludes that in the near future an important amount of wind turbines will use a direct drive train system, but their top mass will increase drastically. The reduction in the weight of the blades and the generator must be one of the main focuses for the future.

Once the Upscaling had been analysed, an Upscaling model was created with the aim of predicting the main characteristics of future upscaled wind turbines based on the data included in the database. The model has some inputs, such as the rotor diameter, wind speed and air density, and it gives as outputs other characteristics of the wind turbine, such as the expected rated power output, the weight and the dimension of different parts. The core of model was created in Matlab, but the database and the interface where the inputs and outputs of the model are visualized were created in Excel.

## 5.1 Future Work

The model calculates the main characteristics of a WT from the data available in the database. Since for some characteristics there is not too much or not enough data, one of the first thing to do will be to try to update the database, either with more wind turbines (prototypes or already in the market), or collecting more data for the WTs present in the database. This last point could not be easy: during this project all manufacturers in the database were contacted with the aim of obtaining more information about their WT, but the vast majority could not contribute for reasons of confidentiality.

If the database is highly updated, a revision of the fits must be done in order to verify if they still represent the trends.

It could be also interesting to perform an analysis of the cost of Upscaled wind turbines in order to point the sector to focus on the reduction of the global cost. One of these sectors is the generator, if the trends continue PMG must reduce their cost in order to be competitive. Other important focus of the WT Upscaling is the study of how the different loads increase while making bigger rotors.

These two last points could be implemented into the model to increase its power.

# Bibliography


[1] Upwind: Design limits and solutions for very large wind turbines. pages 1–108, March 2011.

[2] 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. *Wiley Online Library*, Volume 15:pp. 3–17, 2012.

[3] J.Helsen, F. Vanhollebeke, D.Vandepitte, and W.Desmet. Some trends and challenges in wind turbine upscaling. *International Conference on Noise and Vibration Engineering ISMA*, Volume 1:pp. 1–16, 2012.

[4] Rafael Romao da Silva Melo and Aristeu da Silveira Neto. Integral analysis of rotors of a wind generator. *Renewable and Sustainable Energy Reviews, Elsevier Ltd.*, Volume 16:pp. 2, March 2012.

[5] Illustration of a wind turbine. `http://en.wikipedia.org/wiki/File:Wind_turbine_int.svg`, 2007. Accessed: 2013-02-18.

[6] J.Ribranti and L.Bertling. Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005. *Institute of Electrical and Electronics Engineers (IEEE)*, Volume 1:pp. 1–8, 2007.

[7] Laboratory for energy conversion. Wind Energy: Glossary. `http://www.lec.ethz.ch/research/wind_energy/Wind_Energy_Glossary`, April 2012. Accessed: 2013-05-10.

[8] F. Oyague. Gearbox modeling and load simulation of a baseline 750-kw wind turbine using state-of-the-art simulation codes. *National Renewable Energy Laboratory*, Volume 1:pp. 18, February 2011.

[9] International Electrotechnical Commission IEC. Keeping turbines spinning in the wind. `http://www.iec.ch/etech/2012/etech_1112/store-1.htm`, November 2012. Accessed: 2013-03-15.

[10] Enercon. `http://www.enercon.de/en-en/21.htm`, 2013. Accessed: 2013-03-22.

[11] European Wind Energy Association. Wind energy - The facts. `http://www.wind-energy-the-facts.org/`, 2009. Accessed: 2013-03-20.

[12] Clipper. `http://www.clipperwind.com`. Accessed: 2013-02-26.

[13] Wenping Cao, Ying Xie, and Zheng Tan. Wind turbine generator technologies. *InTech*, November 2012. Edited by Dr. Rupp Carriveau.

[14] Mechanical Engineering Blog. Modern wind turbine: Common AC generator types, 2011. Accessed: 2013-05-20.

[15] Wind power plant Blog. Electricity generation of wind power plant, 2009. Accessed: 2013-04-20.

[16] Marcelo Gustavo Molina and Juan Manuel Gimenez Alvarez. Technical and regulatory exigencies for grid connection of wind generation, wind farm - technical regulations, potential estimation and siting assessment. *INTECH*, june 2011.

[17] Nizar Molaeb. Wind turbine swept area. http://renewable-solar-energy.blogspot.se/2011/07/wind-turbine-swept-area.htm, 2011. Accessed: 2013-04-30.

[18] PelaFlow Consulting. Wind power program. http://www.wind-power-program.com/. Accessed: 2013-04-28.

[19] A.R Jha. *Wind Turbine Technology.* CRC Press Taylor & Francis Group, 2011.

[20] Alexander M. Gorlov Alexander N. Gorban and Valentin M. Silantyev. Limits of the turbine efficiency for free fluid flow. *Journal of Energy Resources Technology*, Volume 123:pp. 1–7, December 2001.

[21] European Committee for Electrotechnical Standardization CENELEC. Wind turbines part 1: Design requirements IEC 61400-1:2005. *National Renewable Energy Laboratory*, Volume 3:pp. 13–89, November 2005.

[22] Zoran Ivanovski. Direct-drive wind turbines. *International Journal of Scientific and Engineering Research*, Volume 2(10):pp. 1–11, 2011.

[23] Martin Fischer. Superconductors on the high seas. *Wind Systems Magazine*, pages pp. 1–6, May 2011.

[24] Martin Fischer. Superconducting seatitan opens up a new path to 10 MW. http://www.renewableenergyworld.com/rea/news/article/2010/10/superconducting-seatitan-opens-path-to-10-mw, October 2010. Accessed: 2013-04-19.

[25] Erik Palmr. The next big thing in wind: Slow wind, huge turbines. http://news.cnet.com/8301-11128_3-10233108-54.html, 2009. Accessed: 2013-05-28.

[26] Wind power engineering & development. World's largest rotor 20% lighter than traditional design. http://www.windpowerengineering.com/design/mechanical/worlds-largest-rotor-20-lighter-than-traditional-design/, February 2013. Accessed: 2013-05-22.

[27] The MathWorks Inc. Matlab and simulink for technical computing. http://www.mathworks.se, 1994-2013.

# List of Figures

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# A Description of the parameters used to evaluate the fit lines

All the information in this section is extracted from the Matlab tutorial: Mathworks [27]. It is important to evaluate the goodness of fit after fitting data. The first step is a visual examination to see if the curve fit follows or not the trend of the points. Then, the fit should be evaluated with respect of the goodness of fit statistics. These goodness of fit statistics are: the R-square ($R^2$), the root mean squared error (RMSE) and the sum of squares due to error (SSE).

## A.1 R-Square

R-square is the square of the correlation between the response values and the predicted response values. It measures how successful the fit is in explaining the variation of the data. R-square can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model [27].
It is defined by the following formula:

$$R^2 = \frac{Sum\ of\ squares\ of\ the\ regression\ (SSR)}{Total\ sum\ of\ squares\ (SST)} \tag{A.1}$$

$$SSR = \sum_{i}^{n} w_i(\hat{y}_i - \bar{y})^2 \tag{A.2}$$

where $w_i$ is the weight assigned to the i point, $\hat{y}_i$ is the estimated $y$ value of the point i and $\bar{y}$ is the mean value of $y$.

$$SST = \sum_{i}^{n} w_i(y_i - \bar{y})^2)^2 \tag{A.3}$$

where $w_i$ is the weight assigned to the i point, $y_i$ is the real $y$ value of the point i and $\bar{y}$ is the mean value of $y$.

## A.2 The sum of squares due to error (SSE)

This statistic measures the total deviation of the response values from the fit to the response values. It is also called the summed square of residuals and is usually labelled as SSE [27].

$$SSE = \sum_{i}^{n} w_i(y_i - \hat{y})^2)^2 \tag{A.4}$$

A value closer to 0 indicates that the model has a smaller random error component, and that the fit will be more useful for prediction.

## A.3 Root mean squared error (RMSE)

This statistic is also known as the fit standard error and the standard error of the regression. It is an estimate of the standard deviation of the random component in the data. An MSE value closer to 0 indicates a fit that is more useful for prediction [27]. It is defined as:

$$RMSE = \sqrt{\frac{SSE}{v}} \tag{A.5}$$

Where $v$ is the difference the number of response values (n) minus the number of fitted coefficients (m) estimated from the response values. [27]

# B Trend lines

The trend lines where calculated, from the data present in the database that was imported to Matlab, using the Curve fitting toolbox present in Matlab.

If nothing is said, all the trend line use a power fit: $f(x) = ax^b$. In the following section the values of the coefficients a and b as well as the $R^2$, SSE and RMSE are given for all the trend lines. The coefficient where calculated within a 95% confidence bounds.

## B.1 Diameter

### B.1.1 Rated power

Table B.1: Fit and goodness parameters: Rated power vs Rotor diameter

| Trend line | a | b | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| All WT | 6.893e-5 | 2.292 | 0.8324 | 2.2e4 | 9.714 |
| Existing WT | 6.739e-4 | 1.789 | 0.996 | 134.2 | 0.7793 |
| Geared DTS with prototypes | 2326e-4 | 2.02 | 0.8995 | 3872 | 5.479 |
| Geared DTS | 3.643e-4 | 1.92 | 0.7656 | 3041 | 5.013 |
| Direct DTS with prototypes | 4.842e-5 | 2.388 | 0.8315 | 1.337e4 | 12.06 |
| Direct DTS | 4.4e-4 | 1.896 | 0.7497 | 3310 | 6.204 |

### B.1.2 Blade length

The equation of the trend line corresponds to a linear polynomial equation: $f(x) = ax + b$).

Table B.2: Fit and goodness parameters: blade length vs Rotor diameter

| Trend line | a | b | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| All WT | 0.4916 | -0.5694 | 0.9982 | 33.08 | 0.564 |

### B.1.3 Tower height

Table B.3: Fit and goodness parameters: Tower height vs Rotor diameter

| Trend line | a | b | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| All WT | 3.413 | 0.6958 | 0.7187 | 2.773e4 | 11.55 |

### B.1.4 Blade mass

Table B.4: Fit and goodness parameters: Blade mass vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.001019 | 1.984 | 0.99907 | 1354 | 6.834 |
| Geared DTS | 0.001255 | 1.934 | 0.9825 | 301.5 | 4.093 |
| Direct DTS | 0.001495 | 1.92 | 0.9305 | 612.2 | 9.352 |

### B.1.5 Rotor mass

Table B.5: Fit and goodness parameters: Rotor mass height vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.01289 | 1.807 | 0.7546 | 6929 | 11.03 |
| Geared DTS | 0.01722 | 1.748 | 0.7369 | 4943 | 10.98 |
| Direct DTS | 0.001208 | 2.31 | 0.8087 | 1702 | 11.44 |

### B.1.6 Nacelle mass

Table B.6: Fit and goodness parameters: Nacelle mass vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.01724 | 1.869 | 0.6706 | 5.053E4 | 27.46 |
| Geared DTS | 0.1065 | 1.45 | 0.8305 | 8473 | 13.29 |
| Direct DTS | 0.01917 | 1.859 | 0.5798 | 1.827E4 | 36.13 |

### B.1.7 Top mass

Table B.7: Fit and goodness parameters: Top mass vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.004883 | 2.249 | 0.8576 | 7.68E6 | 370.3 |
| Geared DTS | 0.06104 | 1.683 | 0.7704 | 1.58e6 | 206.6 |
| Direct DTS | 0.01014 | 2.088 | 0.6169 | 2.098e6 | 401.7 |

### B.1.8 Root and tip chord

Table B.8: Fit and goodness parameters: Root chord speed vs blade length

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.237 | 0.6895 | 0.5716 | 6.271 | 0.5745 |

Table B.9: Fit and goodness parameters: Root chord speed vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.1388 | 0.6988 | 0.5591 | 6.56 | 0.5727 |

Table B.10: Fit and goodness parameters: Root chord speed vs tip chord

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 4.069 | 0.4711 | 0.5516 | 3.515 | 0.5653 |

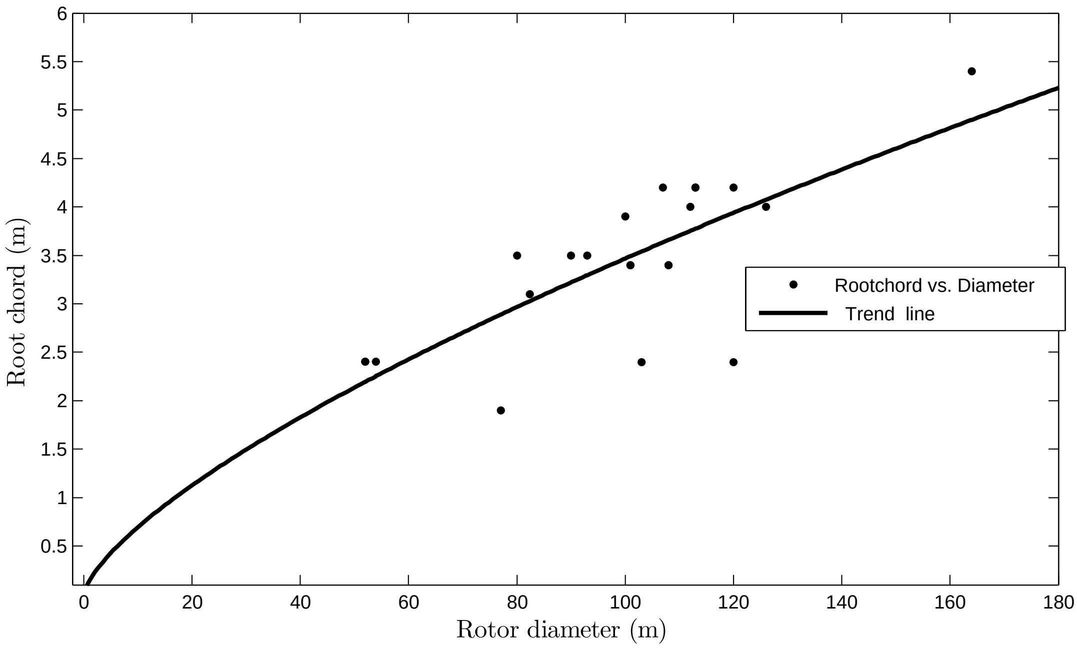


Figure B.1: *Evolution of the root chord with respect of the rotor diameter*

### B.1.9 Maximum rotor speed

Table B.11: Fit and goodness parameters: Maximum rotor speed vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 793.7 | -0.8504 | 0.9425 | 498.4 | 1.922 |
| Existing WT | 794.7 | -0.8507 | 0.9421 | 488.5 | 1.931 |
| Geared DTS with prototypes | 894 | -0.8753 | 0.7381 | 270.6 | 1.995 |
| Geared DTS | 917.9 | -0.8814 | 0.7182 | 270.1 | 2.023 |
| Direct DTS with prototypes | 854.2 | -0.8736 | 0.9787 | 154.4 | 1.661 |
| Direct DTS | 858 | -0.8748 | 0.9789 | 114.3 | 1.65 |
| Hybrid DTS | 487.1 | -0.7166 | 0.9103 | 11.43 | 1.196 |
| Class I WT | 1008 | -0.9037 | 0.8886 | 83.05 | 1.787 |
| Class II WT | 796.8 | -0.8508 | 0.9644 | 241 | 2.021 |
| Class III WT | 758.4 | -0.8351 | 0.9552 | 283.3 | 2.661 |
| Class S WT | 854.7 | -0.8631 | 0.939 | 12.95 | 1.61 |

### B.1.10 Minimum rotor speed

Table B.12: Fit and goodness parameters: Minimum rotor speed vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 188.8 | -0.7081 | 0.6 | 603.2 | 2.271 |
| Existing WT | 188.5 | -0.7076 | 0.5978 | 600.7 | 2.285 |
| Geared DTS with prototypes | 2277 | -1.22 | 0.642 | 156 | 1.684 |
| Geared DTS | 2670 | -1.256 | 0.6355 | 152.1 | 1.694 |
| Direct DTS with prototypes | 260.1 | -0.8212 | 0.864 | 126.8 | 1.577 |
| Direct DTS | 259.8 | -0.821 | 0.863 | 126.8 | 1.593 |
| Hybrid DTS | 80.87 | -0.585 | 0.647 | 3.444 | 0.6561 |
| Class I WT | 214.2 | -0.7303 | 0.3489 | 147.4 | 2.478 |
| Class II WT | 180 | -0.6962 | 0.699 | 299.4 | 2.377 |
| Class III WT | 171 | -0.6822 | 0.7145 | 245.6 | 2.728 |

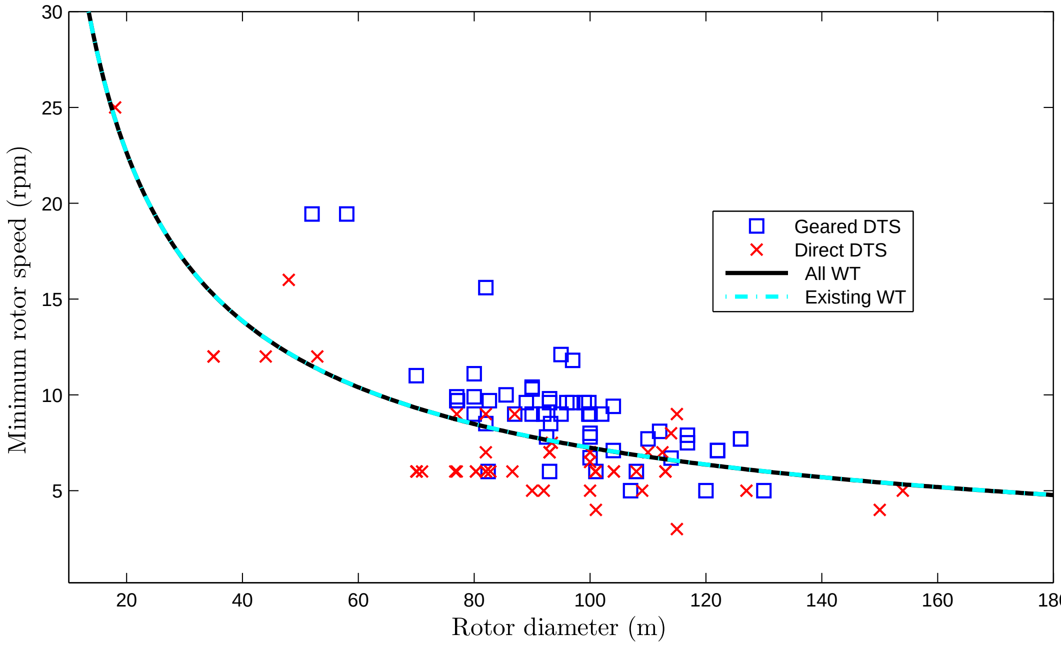


Figure B.2: *Evolution of the minimal rotor speed with respect of the rotor diameter: All WT*

### B.1.11 Tip speed

Table B.13: Fit and goodness parameters: Tip speed vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 32.94 | 0.1999 | 0.5236 | 3245 | 7.899 |

### B.1.12 Nominal power

Table B.14: Fit and goodness parameters: Nominal power vs Rotor diameter

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 0.004043 | 1.683 | 0.7194 | 1507 | 2.773 |
| Geared DTS | 0.003468 | 1.71 | 0.7327 | 486.1 | 2.162 |
| Direct DTS | 0.009875 | 1.496 | 0.5325 | 816.8 | 3.368 |

## B.2 Power

### B.2.1 Blade mass

Table B.15: Fit and goodness parameters: Blade mass vs Rated power

| Trend line | a | b | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| All WT | 3.478 | 1.078 | 0.9517 | 64.84 | 1.495 |
| Geared DTS | 3.92 | 0.9728 | 0.9436 | 17.35 | 0.9818 |
| Direct DTS | 4.247 | 0.8174 | 0.9398 | 530.5 | 8.705 |

### B.2.2 Nacelle mass

Table B.16: Fit and goodness parameters: Nacelle mass vs Rated power

| Trend line | a | b | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|
| All WT | 30.39 | 1.192 | 0.9065 | 1.434E4 | 14.63 |
| Geared DTS | 35.34 | 1.013 | 0.9343 | 3284 | 8.271 |
| Direct DTS | 30.57 | 1.146 | 0.8267 | 7535 | 23.2 |

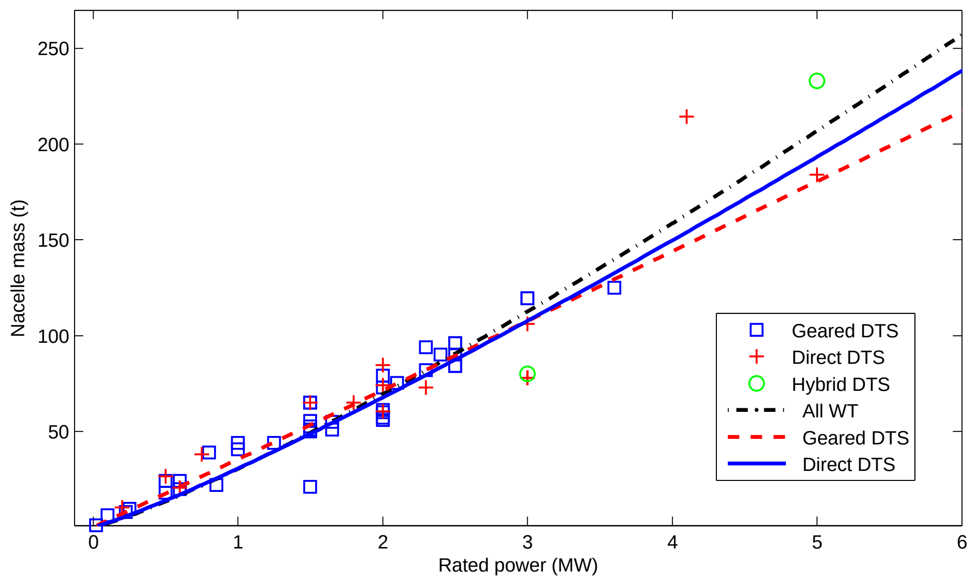


Figure B.3: *Evolution of the nacelle mass with respect of the rated power*

Table B.17: Fit and goodness parameters: Top mass vs Rated power

### B.2.3 Top mass

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 53.51 | 1.088 | 0.9536 | 2.015e4 | 19.14 |
| Geared DTS | 54.01 | 1.092 | 0.9263 | 6565.8 | 13.32 |
| Direct DTS | 52.79 | 1.032 | 0.931 | 5146.2 | 19.9 |

### B.2.4 Maximum rotor speed

Table B.18: Fit and goodness parameters: Maximum rotor speed vs Rated power

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 23.16 | -0.374 | 0.9078 | 792.8 | 2.423 |
| Existing WT | 23.16 | -0.3743 | 0.906 | 787.2 | 2.451 |
| Geared DTS with prototypes | 23.97 | -0.4487 | 0.7342 | 274.6 | 2.009 |
| Geared DTS | 24.05 | -0.4555 | 0.7158 | 272.4 | 2.032 |
| Direct DTS with prototypes | 23.2 | -0.3717 | 0.9392 | 439.5 | 2.802 |
| Direct DTS | 23.18 | -0.3722 | 0.9377 | 434.1 | 2.862 |
| Hybrid DTS | 26.22 | -0.368 | 0.9635 | 4.649 | 0.17623 |
| Class I WT | 26.55 | -0.4422 | 0.7591 | 179.6 | 2.628 |
| Class II WT | 22.9 | -0.3761 | 0.9497 | 340.6 | 2.403 |
| Class III WT | 22.61 | -0.3798 | 0.9472 | 325.9 | 2.854 |
| Class S WT | 23.88 | -0.4259 | 0.7877 | 45.05 | 3.002 |

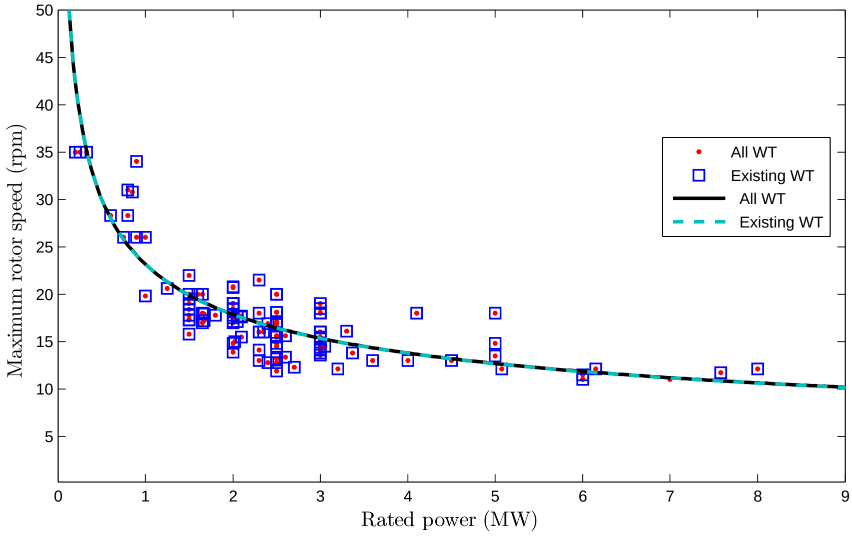


Figure B.4: *Evolution of the maximum rotor speed with respect of the rated power: All WTs*

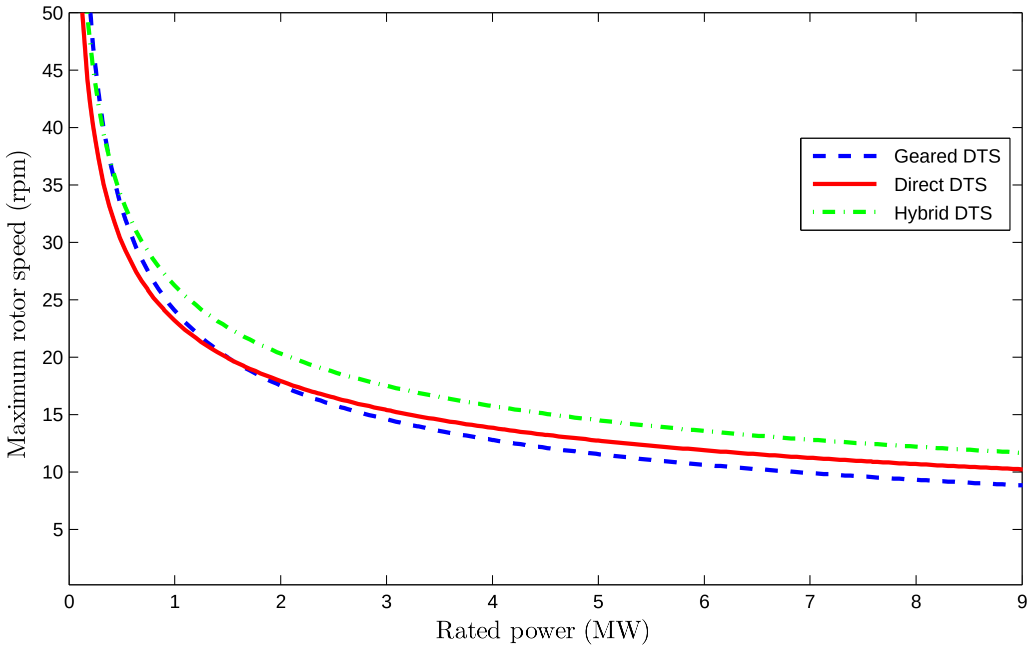


Figure B.5: *Evolution of the maximum rotor speed with respect of the rated power: different DTS*

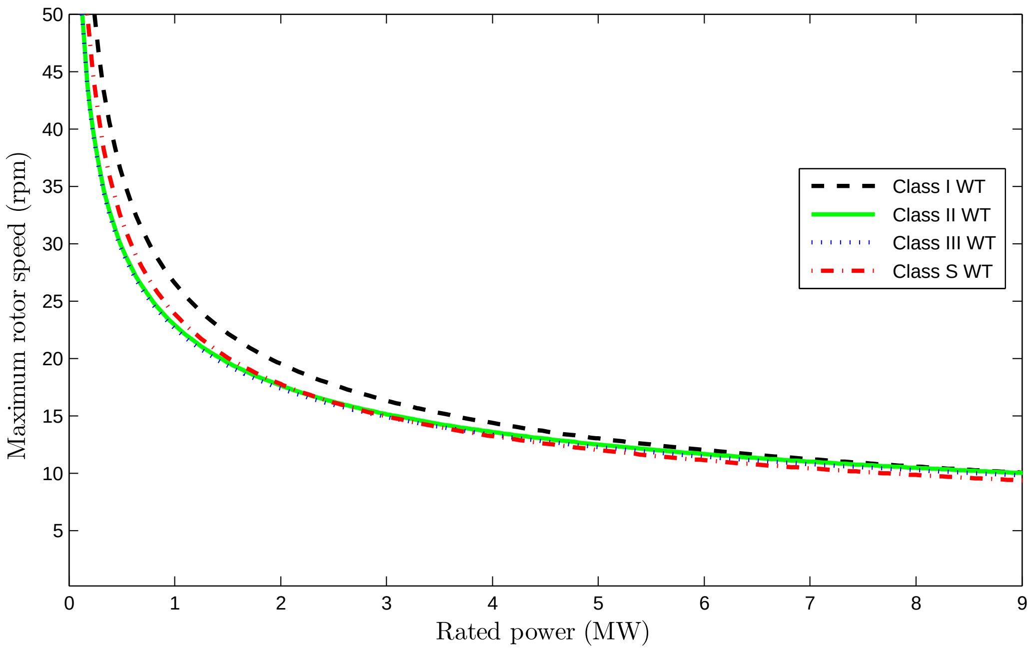


Figure B.6: *Evolution of the maximum rotor speed with respect of the rated power: different WT classes*

## B.3 Other

### B.3.1 Blade mass vs blade length

| **Trend line** | **a** | **b** | $R^2$ | **SSE** | **RMSE** |
|---|---|---|---|---|---|
| All WT | 15.62 | 0.5008 | 0.9784 | 133.1 | 2.579 |

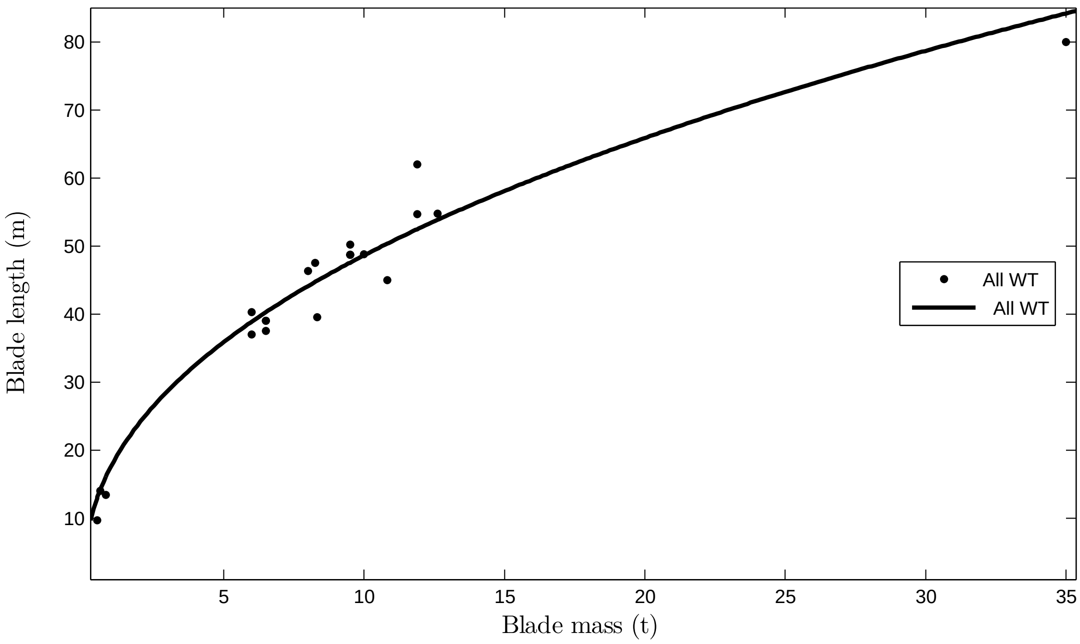


Figure B.7: *Evolution of the blade mass with respect of the blade length*

# C Model tutorial

This is the data included in the README file in the model.

### DESCRIPTION

The model calculates the main characteristics of a WT based on a database. The model is used to calculate future upscaled wind turbines. The model used two software: Matlab and Excel. Inputs of the model: rotor diameter, wind speed and air density. Outputs of the model: rated power, nominal power, nominal efficiency, minimum and maximum rotor speed, blade length, tip and root chord, tip speed, tower height, blade mass, rotor mass, nacelle mass and top mass. The model allows to calculate the outputs following the different category trend lines: All WT, Existing WT, Geared DTS, Direct DTS, Hybrid DTS, Geared DTS with prototypes and Direct DTS with prototypes.

### INSTALL NOTES

In order to use the model MATLAB and Microsoft Excel should be installed in the computer. Microsoft Excel is not mandatory; other similar software can be used. The first thing to do is extract the file *Upcaling_model.zip*. Once extracted you should have two Excel files (*WT_calculation_tool* and *WT_database*) and several Matlab files (30 in total).

### USER MANUAL

Here is the step by step tutorial to run the model:

1- Open the "*WT_database*" file

2- Update the database as your own, without changing the order of the colons.

3- Close the "*WT_database*" file.

4- Open the file main.m with Matlab and run it (choose Change Folder).

5- Now the model will start to ask you some questions.

6- The first time you run the model you should answer yes to the question "Do you want to import the data from the data base".

7- Now you have 3 options: just plot the data from the database and the trend lines, just import the parameters of the trend lines to the file "*WT_calculation_tool*" or do both.

8- The last question is to choose if you want to compare the characteristics of the Wind turbine with respect of the rotor diameter, the rated power or do both comparisons. If you want to update the fit parameters to the "WT_calculation_tool" you must select at least choose "Rotor diameter". Make sure that you have closed the "*WT_calculation_tool*", otherwise the model will not be able to import the data and will not run.

9- Now Matlab starts to import the data from the database and do all that you have specified. It takes a while to calculate everything. A sound wills pop-up when the model had finished.

10- Once Matlab has finished you can do two things. The first one is to analyse the plots and modify them as you want with the "Plot tools" included in Matlab. The other option is to open the "*WT_calculation_tool*" file and introduce the inputs parameters in order to calculate the characteristics of a WT.