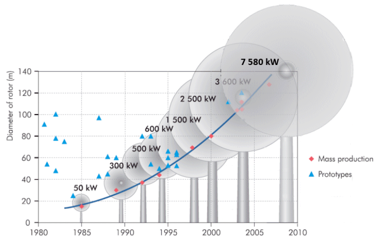
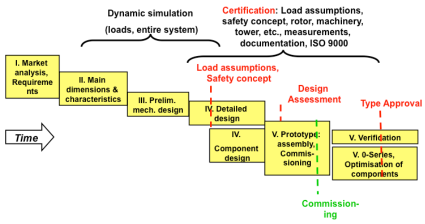
# Design of Wind Energy Systems
# Summer Term 2016

Carl von Ossietzky Universität Oldenburg
ForWind Center for Wind Energy Research




# Lecture 1: Introduction to Wind Turbine Design

Typical wind turbine design process




*Prof. Dr. Martin Kühn*

*ForWind – Wind Energy Systems*

## Contents

I. Organisation of lecture

II. Recent market trends in wind turbines design

III. Design process of wind turbines

IV. Techno-economic optimisation of wind turbines
- Approach 1: Turbine design for lowest cost of energy
- Approach 2: Turbine design for series production
- Approach 3: Turbine design for high penetration of wind power

# References


- C. Ender, Wind Energy Use in Germany – Status 31.12.2010, DEWI Mag. 40, Feb. 2012
- J.P. Molly, Rated Power of Wind Turbines – What is Best?, DEWI Mag. 38, Feb. 2011
- EWEA, Wind in power: 2012 Euroopean Statistics, Feb. 2013
- Deutsche WindGuard, Status of wind energy development in Germany, 2012
- R. Gash, J. Twele, Wind Power Plants. Fundamentals, Design Construction and Operation, 2nd ed., Springer 2012








# I. Organisation of lecture

Six modules as:

- ✓ 15 lectures
- ✓ 6 class tutorials
- ✓ 7 CIP-tutorials

= 28 sessions

Expected effort:

- ✓ ~30h / 1 ECTS
- ✓ 6 ECTS
- ✓ ~180 h / semester

= ~10 h / week

plus presentation & exam

| Module | Day | Date | Tuesday 12:15 - 13:45 h Venue: W01-0-008 | Tuesday 14:15 – 16:45 h Venue: W01-0-008 |
|---|---|---|---|---|
| 1. Selection of turbine main parameters | 1 | 14.04 | Lecture 1: Introduction to wind turbine design, organisational affairs [MK] | Lecture 2: Introduction to aeroelastic simulations, quiz & outlook [LVT] |
| | 2 | 21.04 | Lecture 3: Cost modelling of wind turbine [MK] | Tutorial 1: Annual energy production & levelized production cost [MK] |
| | 3 | 28.04 | CIP-Tutorial 1: Introduction, selection of main characteristics & rotor design [LVT] | |
| 2. Rotor design & BEM | 3 | 28.04 | | Lecture 4: Repetition of basic disk actuator momentum theory & BEM [LVT] |
| | 4 | 05.05 | Tutorial 2: Blade element momentum [LVT] | CIP-Tutorial 2: Advanced blade element momentum theory – Corrections [LVT] |
| | 5 | 12.05 | | Lecture 5: Rotor design [MK] |
| 3. Control & characteristic curves | 5 | 12.05 | Lecture 6: Control & measurements of dynamic loads [MK] | |
| | 6 | 19.05 | CIP-Tutorial 3: Dimensional and non-dimensional performance curves [JJT] | Lecture 7: Wind turbine control and certification requirements [BK] |
| | 7 | 26.05 | Lecture 8: Advanced wind turbine controls [MK] | |
| 4. Wind turbine dynamics | 7 | 26.05 | | Lecture 9: Dynamic loading and system dynamics [MK] |
| | 8 | 02.06 | Tutorial 3: Dynamics and Campbell diagram [MK] | CIP-Tutorial 4: Tower design and modal analysis [LVT] |
| 5.External conditions | 9 | 09.06 | Lecture 10: Wind field modelling [JJT] | Lecture 11: Wind turbine performance in wake conditions [JJT] |
| | 10 | 16.06 | CIP-Tutorial 5: Wind field & wake modelling [LVT] | Lecture 12: Wind farm flow and performance [JJT] |
| | 11 | 23.06 | Lecture 13: Offshore loads (specific effects) [MK] | |
| 6. Load analysis | 11 | 23.06 | | Lecture 14: Design load cases, certification [MK] |
| | 12 | 30.06 | Tutorial 4: Load calculation and fatigue analysis [MK] | Lecture 15: Extreme loads and component design [MK] |
| | 13 | 07.07 | CIP-Tutorial 6: Fatigue and extreme loads, power spectral density and load spectra [JJT] | Tutorial 5: Component design [MK] |
| | 14 | 14.07 | CIP-Tutorial 7: Simulation wrap-up [JJT] | Course summary [MK, JJT] |

See actual schedule 2016 on Stud.IP

(optional) 1 day excursion to WT manufacturer or similar

# Module summary

| Nr. | Module | Learning objective |
|---|---|---|
| 1 | Selection of turbine main parameters | Understand how and be able to select the main parameters of a wind turbine for a given site |
| 2 | Rotor design & BEM | Understand how and be able to design a wind turbine rotor blade using BEM theory |
| 3 | Control & characteristic curves | Understand the impact of characteristic curves and different control strategies and be able to adjust these characteristics for a specific turbine design |
| 4 | Wind turbine dynamics | Understand wind turbine dynamics and modal analysis and be able to tailor the dynamics |
| 5 | External conditions | Understand the impact of external conditions (wind, wakes, waves) on wind turbines |
| 6 | Load analysis | Understand how and be able to determine main wind turbine loads and execute an exemplary component design |

Main objective: Be able to derive the conceptual design of a wind turbine at a given site according to international design standard



# Module feedback / evaluation

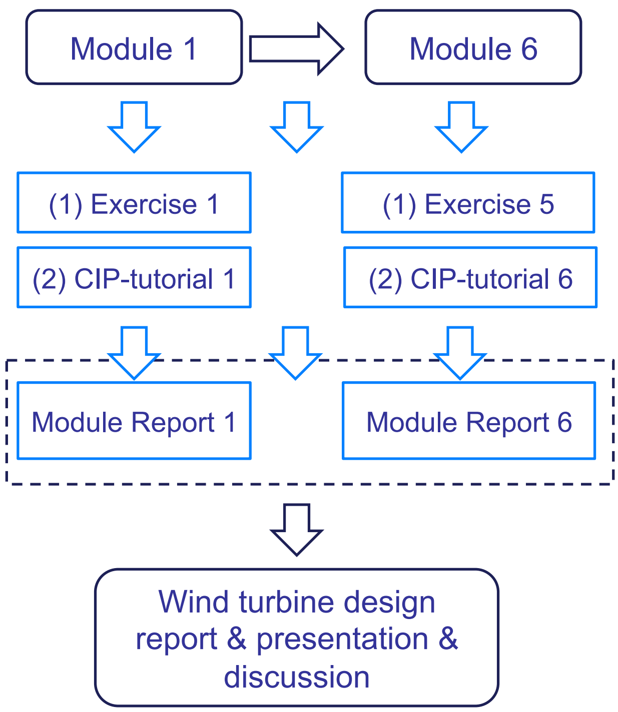
**Quality control**
(in groups of 2 students, feedback by tutors)

(1) Class tutorials: 5 exercises

(2) CIP-tutorial: 6 intermediate module reports

**Evaluation**
(in groups of 2 students)

- Wind turbine design report (collection of corrected module reports + introduction + conclusions) (60%)
- Presentation on design report (15 min.) + discussion on report and background (30 min.) (40%)



# Module 1. Selection of turbine main parameters

| Criteria | Description |
|---|---|
| Objective | Understand how and be able to select the main parameters of a wind turbine for a given site |
| Requisite | Basic knowledge of wind energy (i.e. lectures „Wind Energy Utilisation“ or „Wind Energy I“ |
| Theory | - Economics of wind turbines<br>- Power curve<br>- Annual energy production (AEP)<br>- Levelized production cost (LPC) |
| Class tutorial | - Estimation of AEP & LPC |
| CIP tutorial | - Introduction to WT simulation codes<br>- Selection of main parameters |
| Outcome (documentation) | - Calculation of AEP & LPC<br>- (Wind turbine) product definition |
| Review (quality control) | - Correction of class tutorial's excercises<br>- Feedback on product definition |



# Module 2. Rotor design & BEM

| Criteria | Description |
|---|---|
| Objective | Understand how and be able to design a wind turbine rotor blade using BEM theory |
| Requisite | Knowledge about main characteristics of a wind turbine<br>Fundamentals about airfoil aerodynamics |
| Theory | - Rotor design<br>- Review of disc actuator & BEM theory<br>- Corrections of BEM theory |
| Class tutorial | - BEM theory calculation |
| CIP tutorial | - Rotor and blade design |
| Outcome (documentation) | - Excercise on BEM theory<br>- Blade design and BEM corrections |
| Review (quality control) | - Correction of class tutorial's excercises<br>- Feedback on rotor and blade design |

# Module 3. Control & characteristic curves

| Criteria | Description |
|---|---|
| Objective | Understand the impact of characteristic curves and different control strategies and be able to adjust these characteristics for a specific turbine design |
| Requisite | Basic knowlege of wind energy systems<br>Fundamentals of control theory |
| Theory | - Wind turbine control (blade pitch, rotor speed)<br>- Dimensional and non-dimensional performance curves<br>- Certification requirements |
| Class tutorial | - No excercise |
| CIP tutorial | - Estimation of non-dimensional performance curves |
| Outcome (documentation) | - Evaluation of optimum point in non-dimensional performance curves |
| Review (quality control) | - Feedback on speed and pitch characteristics and non-dimensional performance curves |





# Module 4. Wind turbine dynamics

| Criteria | Description |
|---|---|
| Objective | Understand wind turbine dynamics and modal analysis and be able to tailor the dynamics |
| Requisite | Basic knowlege of wind energy systems<br>Fundamentals of dynamics |
| Theory | - Dynamic loading on wind turbines<br>- Modal analysis & Campbell diagram<br>- Introduction to tower design |
| Class tutorial | - Modal analysis & its impact on tower design |
| CIP tutorial | - Tower design, eigenfrequencies and Campbell diagram |
| Outcome (documentation) | - Tower design hand-calculation<br>- Tower design for simulation codes |
| Review (quality control) | - Correction of class tutorial's excercises<br>- Feedback on wind turbine dynamics |



CARL VON OSSIETZKY universität OLDENBURG

# Module 5. External conditions

| Criteria | Description |
|---|---|
| Objective | Understand the impact of external conditions (wind, wakes, waves) on wind turbines |
| Requisite | Basic knowlege of wind energy systems<br>Fundamentals of stochastics, hydrodynamics |
| Theory | - Wind field modelling<br>- Wake modelling<br>- Offshore loads |
| Class tutorial | - No excercise |
| CIP tutorial | - Wind field and wake modelling according to IEC standard |
| Outcome (documentation) | - Wind field modelling |
| Review (quality control) | - Feedback on assumed external conditions |



# Module 6. Load analysis

| Criteria | Description |
|---|---|
| Objective | Understand how and be able to determine main wind turbine loads and execute an exemplary component design |
| Requisite | Knowledge about dynamics of wind turbines, controls and impact of external conditions |
| Theory | - Design load cases and certification<br>- Fatigue and extreme loads<br>- Component design |
| Class tutorial | - Rainflow counting and load estimation<br>- Component design e.g. tower |
| CIP tutorial | - Fatigue, extreme loads and power spectral |
| Outcome (documentation) | - Load analysis and component design<br>- Design envelope for wind turbine |
| Review (quality control) | - Correction of class tutorial's excercises<br>- Feedback on load analysis and component design |

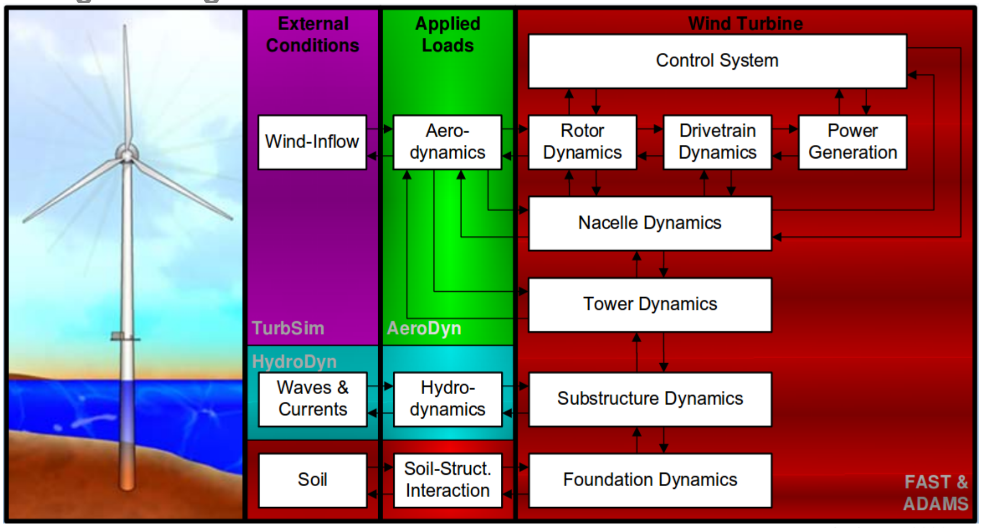
# Wind turbine design simulation codes of NREL

✓ **NREL codes**

- Turbsim, AeroDyn & FAST
- https://wind.nrel.gov/designcodes/

✓ **Matlab scripts**

- stud.IP




Jonkman, 2008

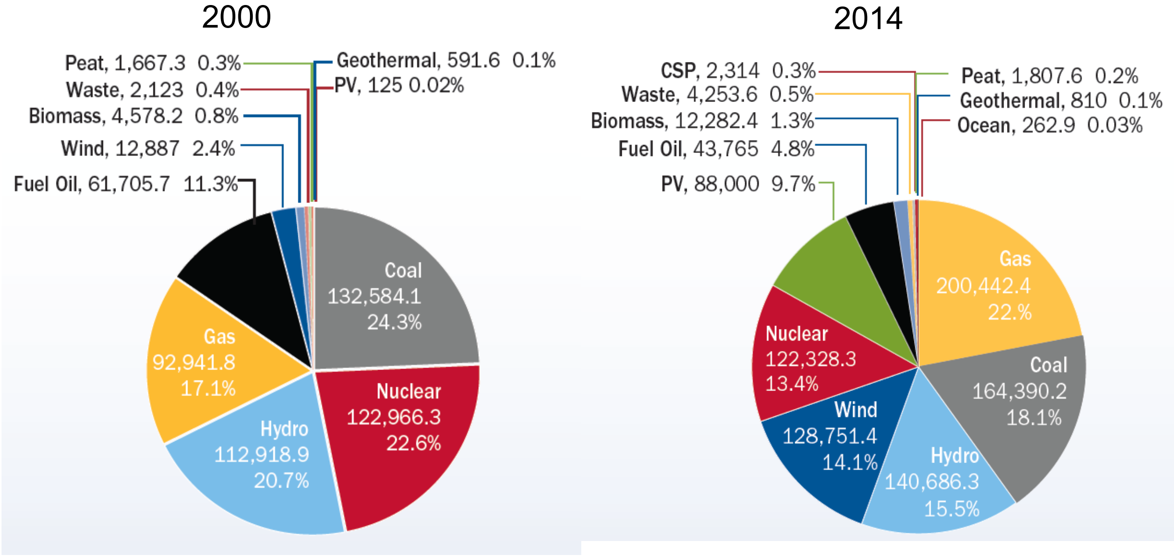


# Section II:
# Recent market trends in wind turbines design

# European power mix

[Fig.: EWEA: Wind in Power – European Statistics 2014]

Installed capacity in MW



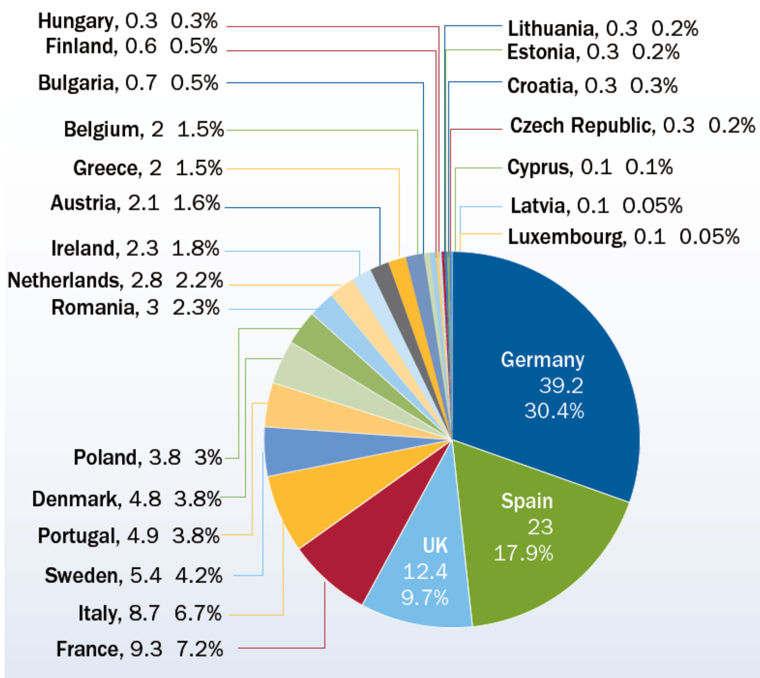

- Renewable capacity increased by 71% from 24.4 % of total power capacity in 2000 to 41.5 % in 2014
- Installed wind power capacity in 2012: 129 GW



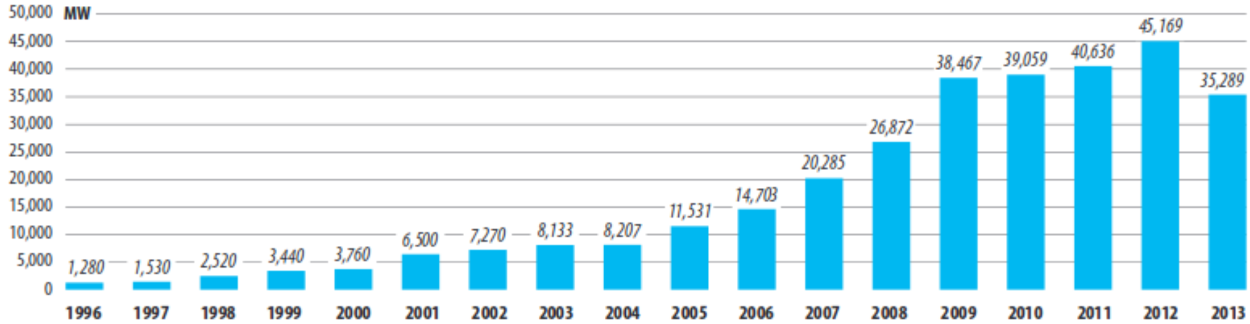
# EU wind energy installed capacity

[Fig.: EWEA: Wind in Power – European Statistics 2014]

Wind power share of installed capacity [GW]



# International market development (annual new installation)




*Source: GWEC Global Wind 2014 Report*



# Recent 5⁺MW offshore wind turbine developments

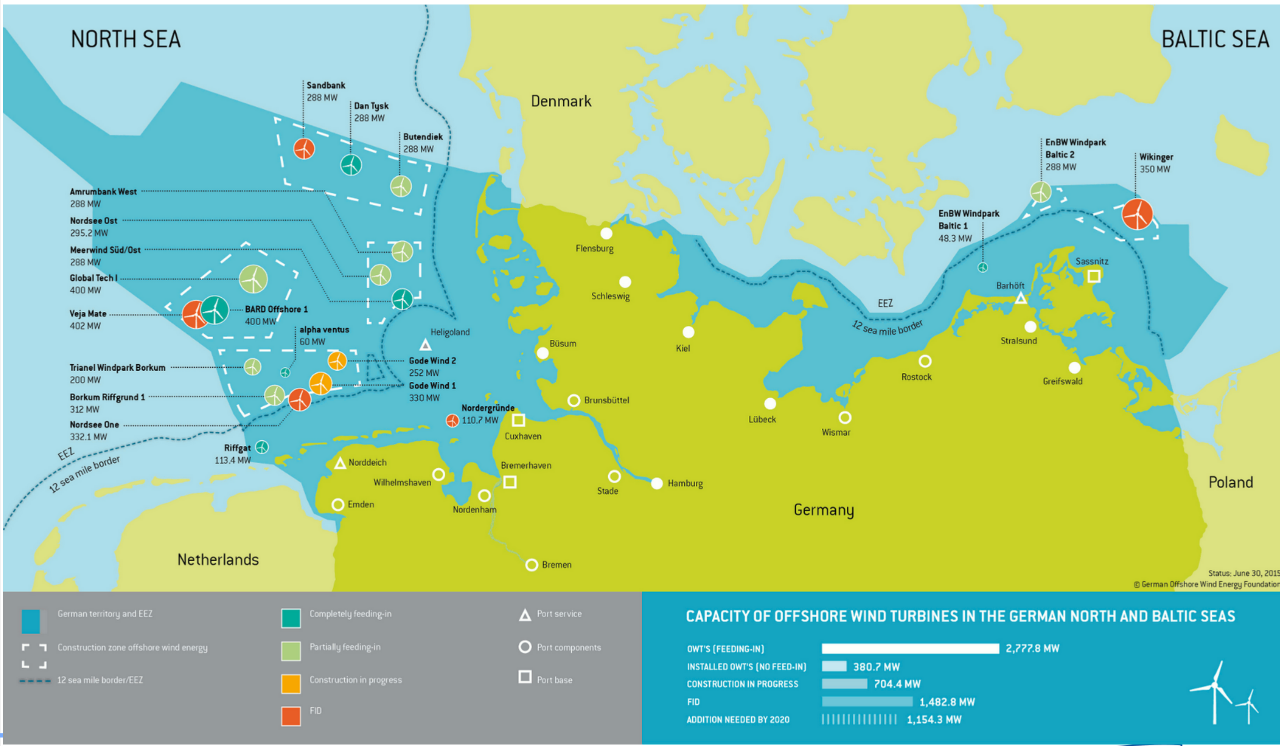
| |  |  |  |  |  |
|---|---|---|---|---|---|
| **Manufacturer** | Alstom | Areva | Gamesa | Hyundai/AMSC | Ming Yang/Aerodyn |
| **Name** | Haliade 150 | Multibrid M5000-135 | G128-5.0 MW | HQ5500 | 6.0SCD |
| **Rated power** | 6 MW | 5 MW | 5 MW | 5.5 MW | 6 MW |
| **Rotor diameter** | 150.8 m | 135 m | 128 m | 140 m | 140 m |
| **Characteristics** | Direct drive, permanent magnet generator, seperate rotor bearing for load transmission | Medium-speed, three-stage hybrid gearbox and integrated rotor | Medium-speed, two-stage planetary gearbox | Compact drive train, three-stage gearbox, main shaft and high-speed generator | Medium-speed, two-stage planetary gearbox, two-blade rotor, downwind |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Mitsubishi | REpower/Senvion | Samsung | Siemens | Vestas | XEMC Darwind |
| SeaAngel | 6.2M152 | S-7.0-171 | SWT-6.0-154 | V164-8.0 | XD115 5MW |
| 7 MW | 6.15 MW | 7 MW | 6 MW | 8 MW | 5 MW |
| 167 m | 152 m | 171 m | 154 m | 164 m | 115 m |
| Fluid power drive train | Upgrade of the 5M, detached drive train concept with three-stage drive | Three-stage overriding drive, medium-speed drive train | Single bearing, direct drive, permanent magnet generator | Rotor, main shaft, gearbox, generator, medium-speed drive train | Single bearing, direct drive, and permanent magnet principle |

[Offshore Wind Industry, issue 01.2014]

# Offshore wind energy in Germany (June 30, 2015)

*Source: German Offshore Wind Energy Foundation*






# Design specification of wind turbines

**Rotor:**
- diameter
- number of blades
- blade profile

**Generator:**
- rated power
- type (synch./asynch.)
- drive-train

**Tower:**
- height
- structure

**Operation:**
- control laws
- installation site

**Goals:**
- Long life cycle
- High reliability
- High availability
- Low cost of energy
- Low maintenance requirements

[Fig: ForWind - WeSys]

# Rotor

Which is a typical rotor diameter for a ...

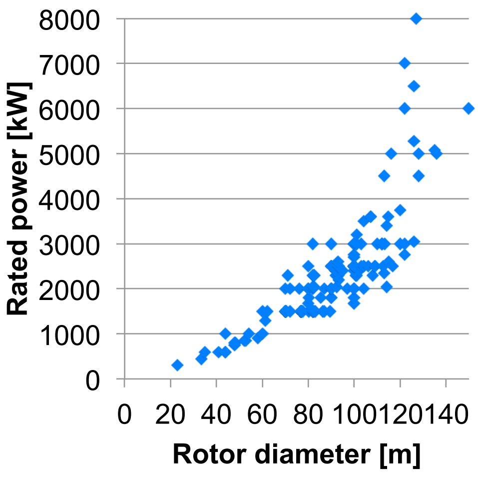
- 800 kW
- 2000 kW
- 5000 kW

...wind turbine?



# Rotor

Which is a typical rotor diameter for a wind turbine?




- 800 kW → (45) … 50 … (60) m
- 2000 kW → (70) … 88 … (100) m
- 5000 kW → (116) …126 … (134) m

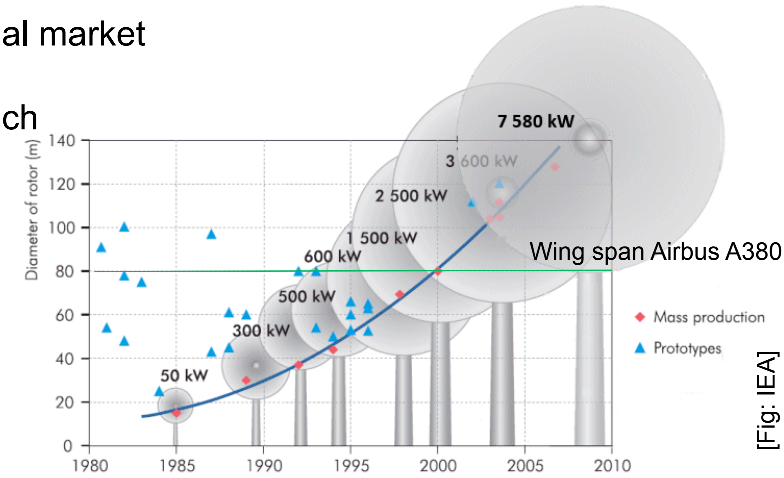
A wind turbine catalog can be found at:
http://www.wind-energy-market.com/

# Rotor

## Beyond the exponential grows of turbine size?

- Size of commercial wind turbines doubled approximately every 4 years during the last 25 years
- since 2005 the grows rate slows down considerably
- however, 10 MW turbines under development

Potential reasons
- strong grow of international market
- procurements issues
- offshore development much slower than expected
- logistics, manufacturing and transportation limits

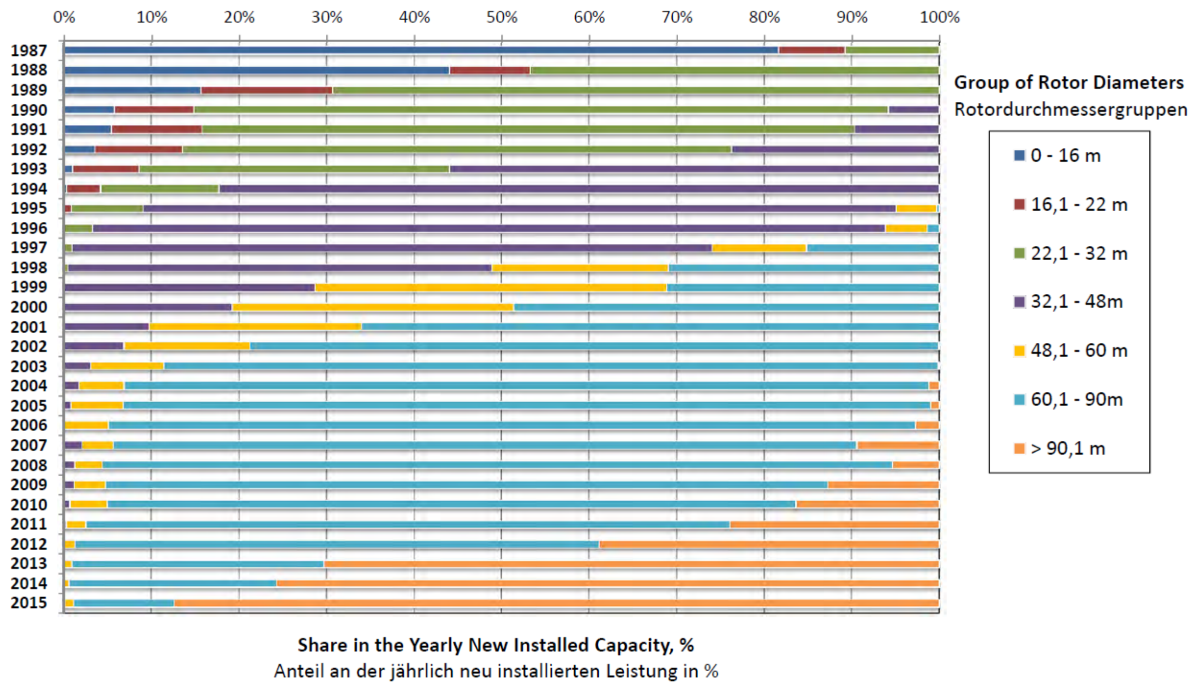



[Fig: IEA]



# Rotor

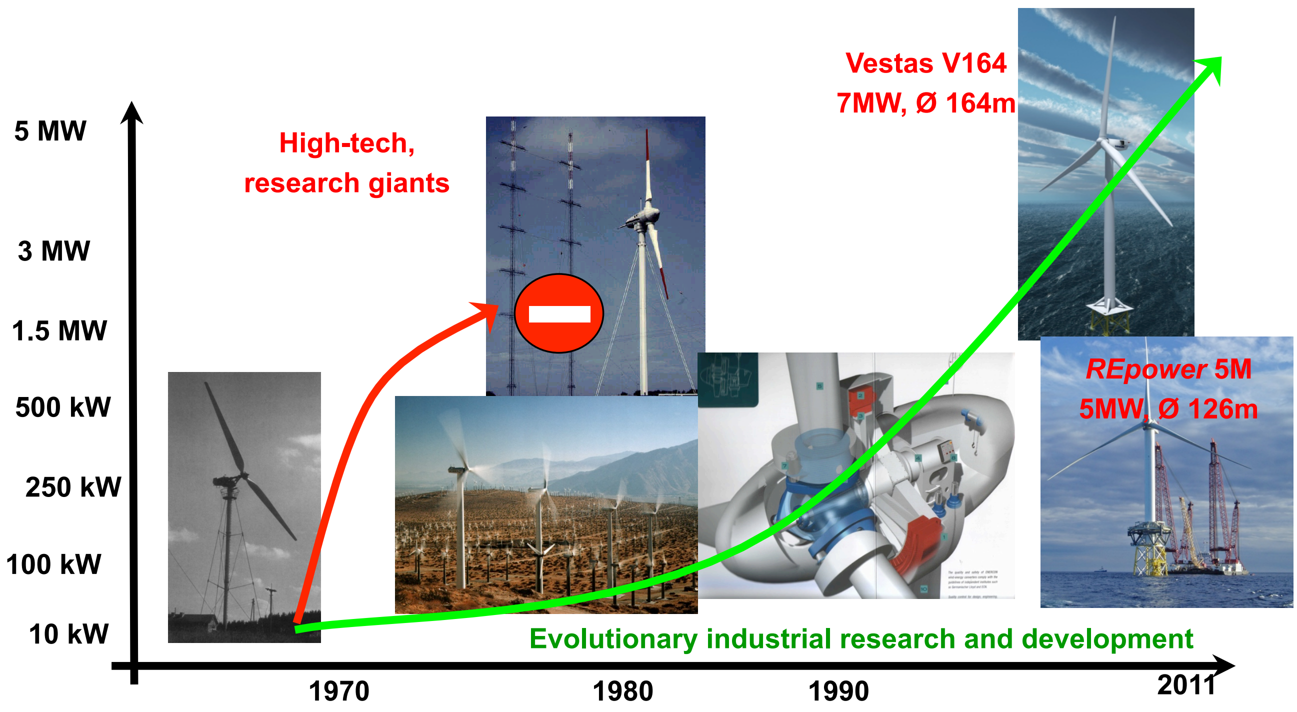
## Share of different rotor size in the annually installed power over the years




*Source: DEWI Magazin No. 47, August 2015*

# Rated power

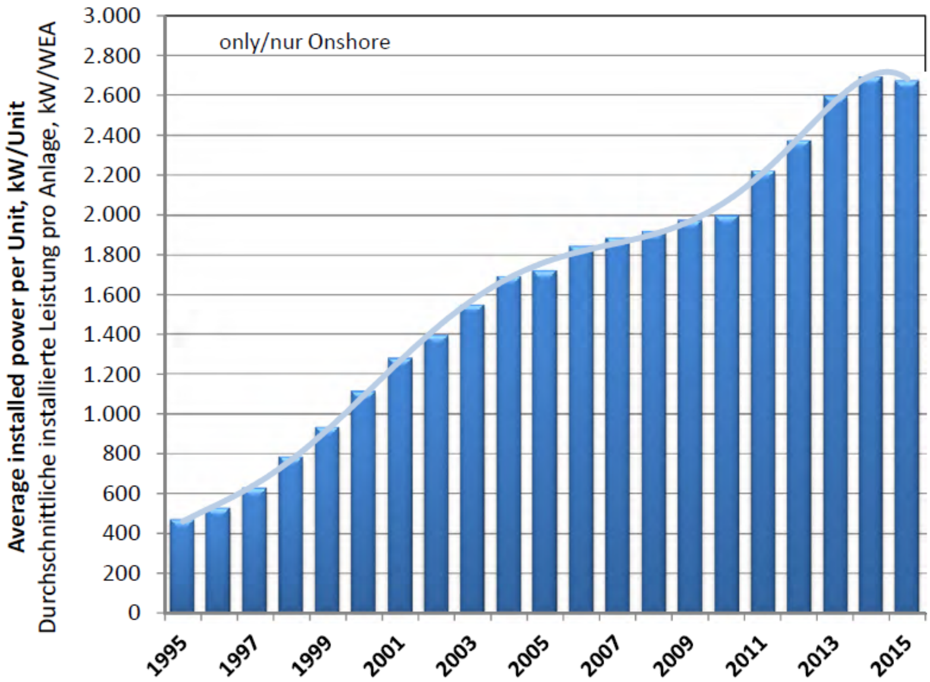
## Gradual technology development is the key of wind energy industry success






# Rated power

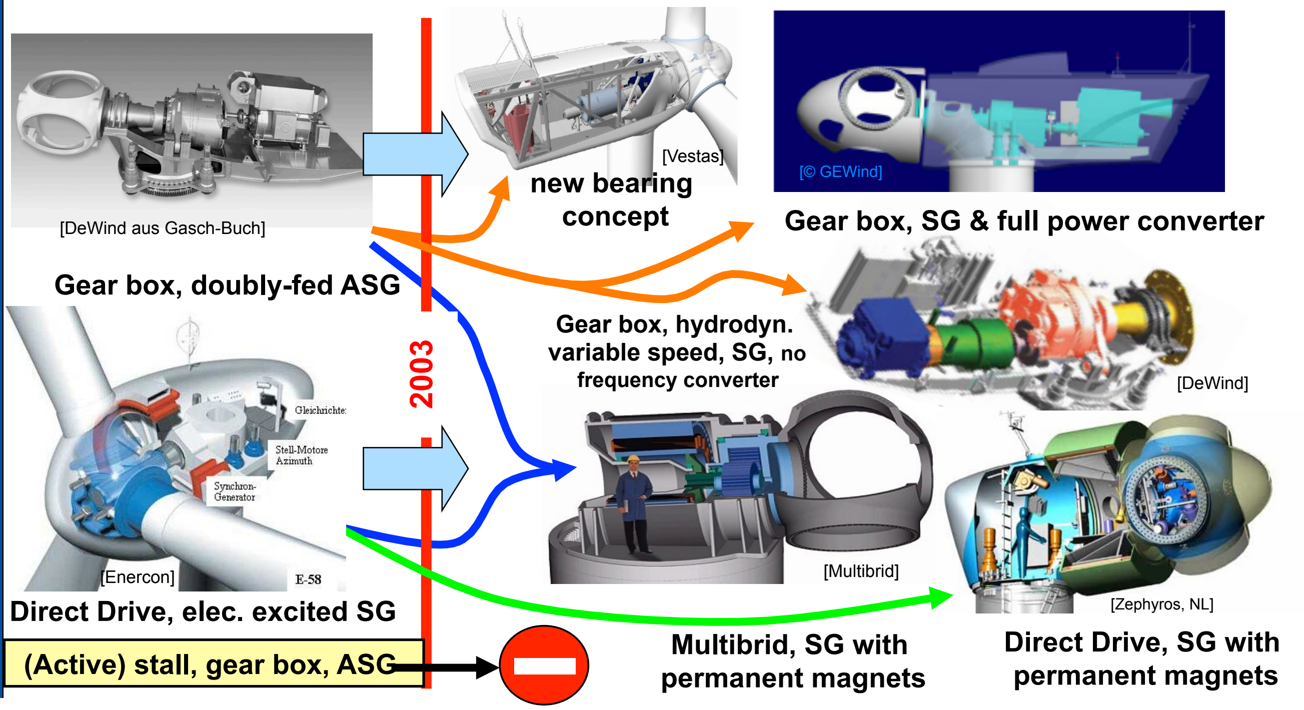
## Increase in average installed power per unit




*Source: DEWI Magazin No. 47, August 2015*

## Drive train and generator

### Development of new concepts in the 2–5 MW class




ASG: asynchronous generator (induction generator)
SG: synchronous generator

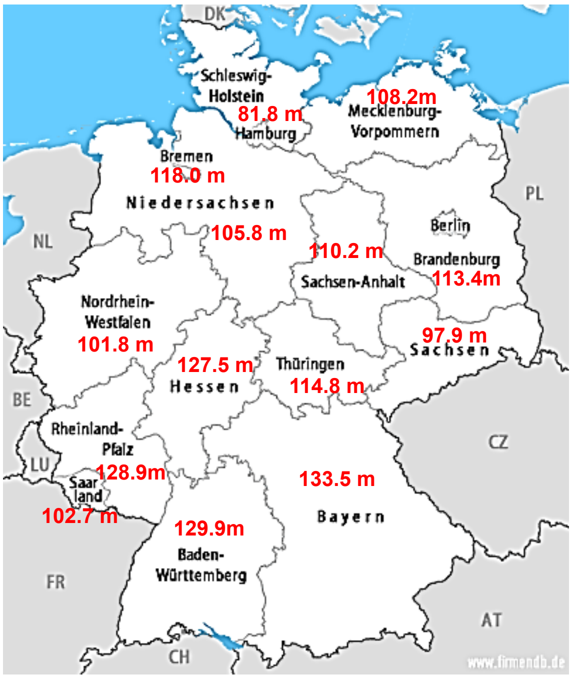
## Tower

### Share of different hub height in the power installed 2011

- Are wind turbine higher inland or in coastal/offshore site?

# Tower

## Average hub height distribution in Germany of new installation in 2012




[Source: Wind Guard 2012]



# Tower

## Share of different hub height in the power installed 2011

- Are wind turbine higher inland or in coastal/offshore site?

  Inland are generally wind turbines' tower taller. In costal/ offshore sites the vertical wind profile reaches the rated wind speed of the turbine at a lower height than onshore. Besides onshore higher towers are required for installation on forest land

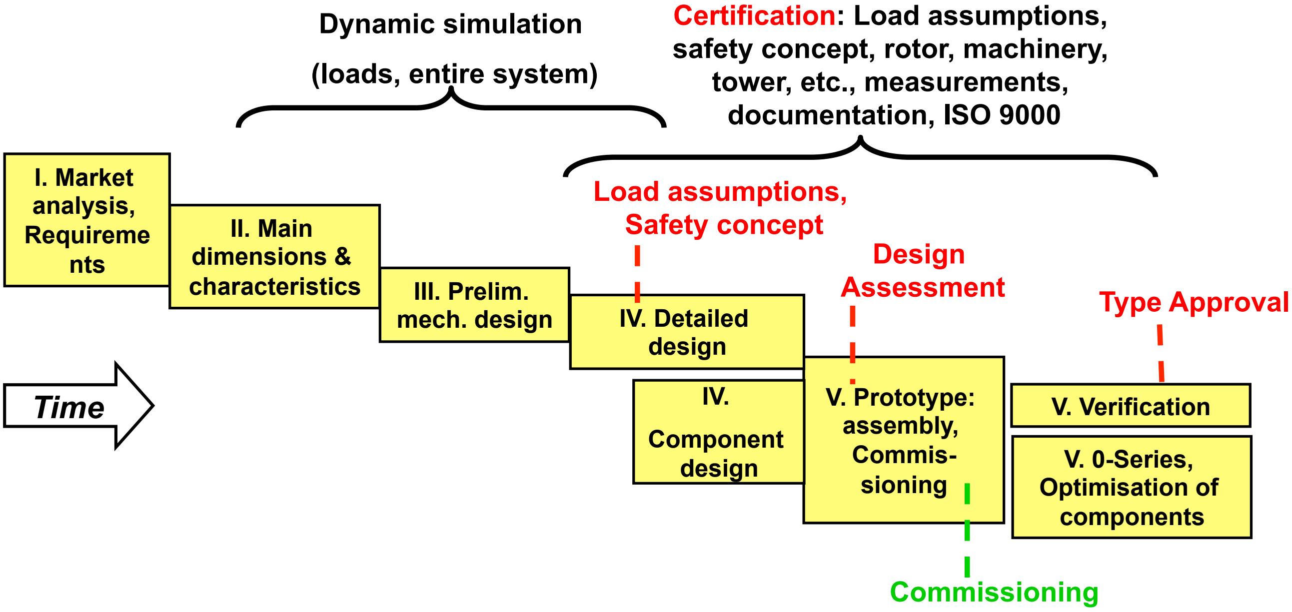
# Section III: Design process of wind turbines

Objectives:

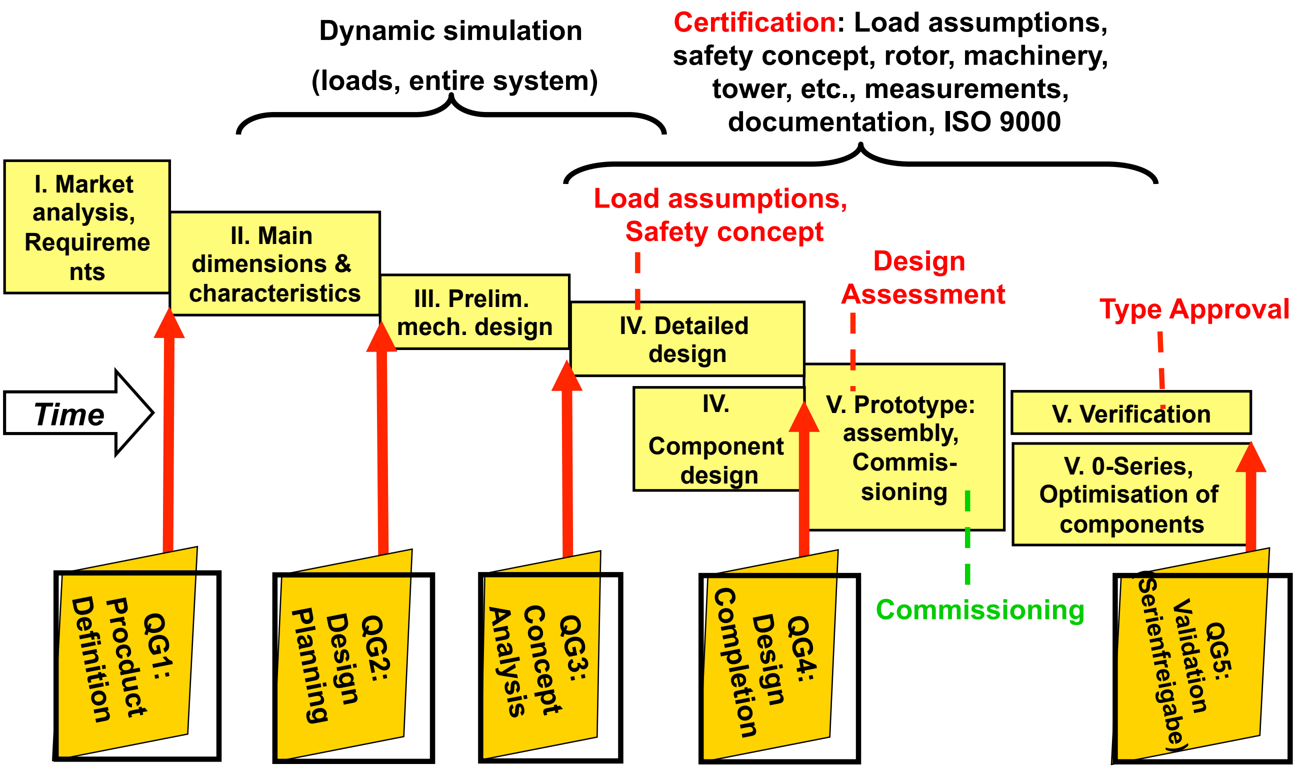
- Understanding the different phases in the design process
- Understanding of dynamic simulation in the context of the wind turbine design process



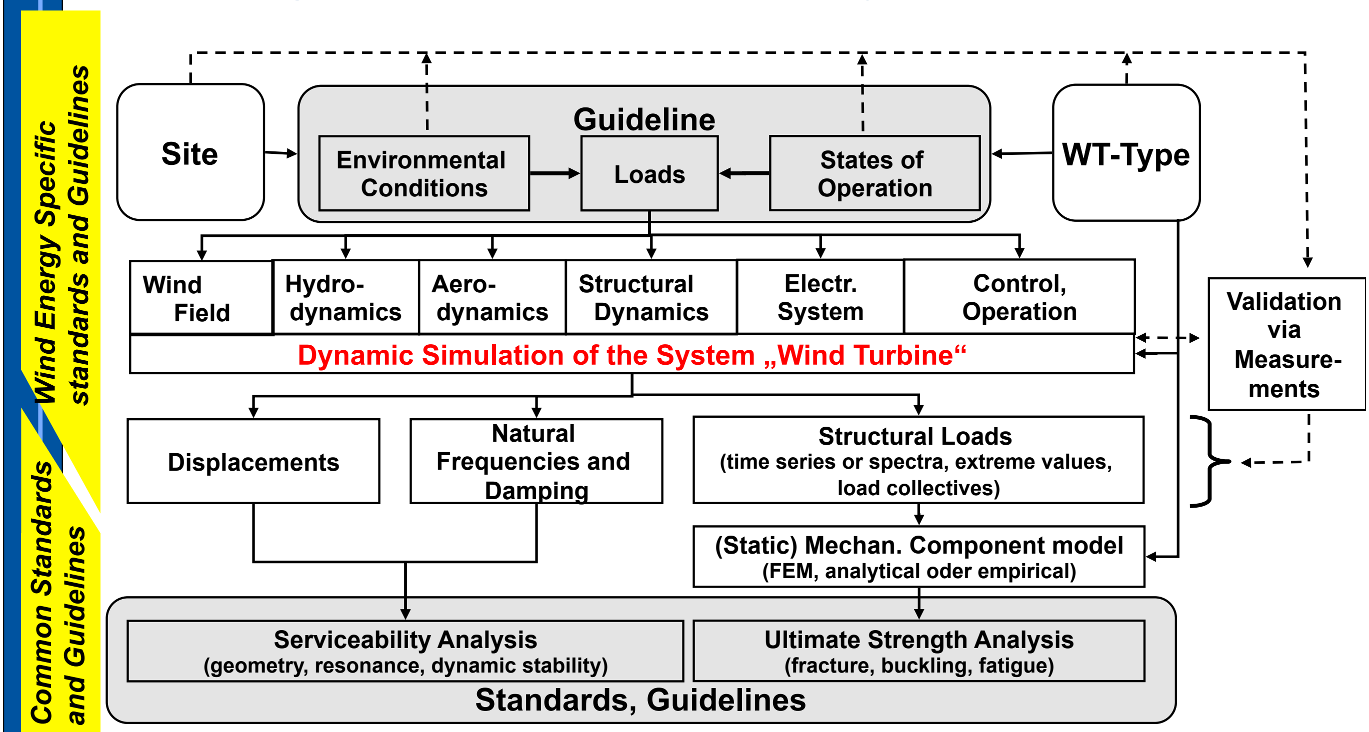
# Typical wind turbine design process



# Quality control with Quality Gate Process: Continuation only after Quality Gate approval




# WT design calculation process & dynamic simulations



## Section IV:
## Techno-economic optimisation of wind turbines

Objective

Understanding some criteria that driven the product development of wind turbines

- Approach 1: Turbine design for lowest cost of energy
- Approach 2: Turbine design for series production
- Approach 3: Turbine design for high penetration of wind power



## Approach 1:
## Turbine design for lowest cost of energy

Assumption:

Feed-in tariff is independent or less dependent from the capacity factor

⇒ lowest cost of energy (€ct/kWh) at a given will be optimum

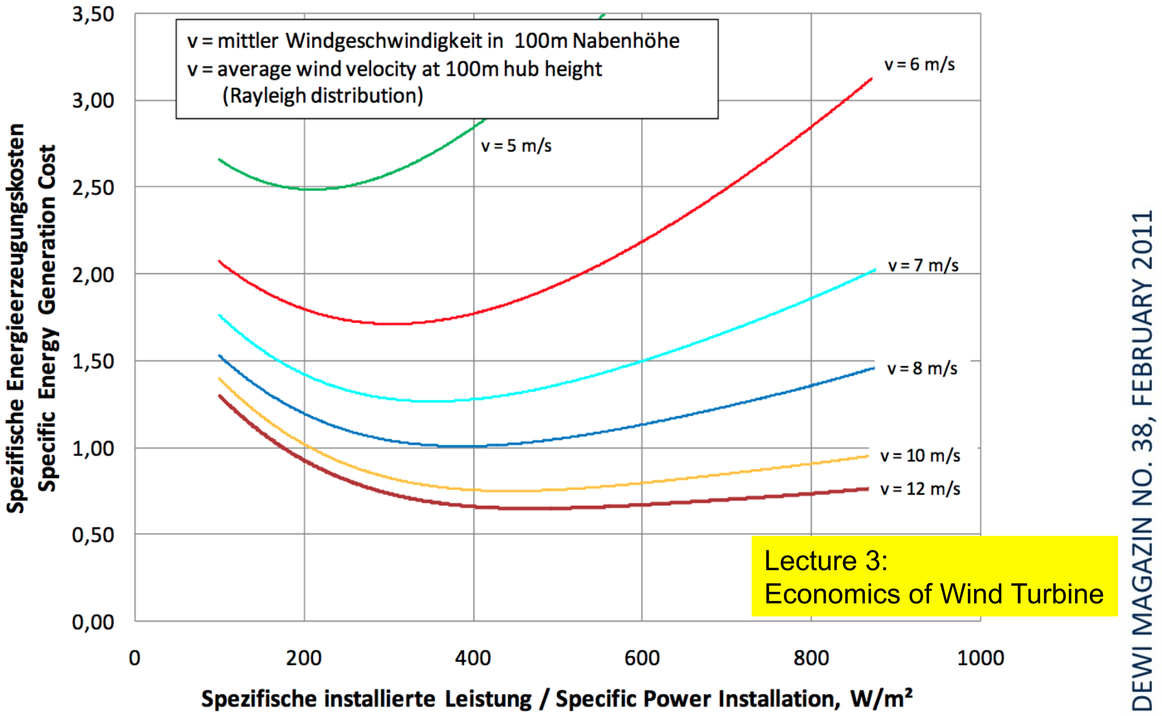
- evaluation of the investment and operational cost of a wind turbine depending on parameters varying about the design point
- evaluation of the annual energy production

⇒ the specific rating should be optimized site specific

Note:

In Germany the feed-in tariff depends on the wind potential at the site i.e. the energy yield of the turbine at the actual site within the first 5 years (so-called “Referenzertrag”)

## Optimum of specific cost of energy




Note: A wind turbine with 400 W/m$^2$ and a site with $v_{ave}$ = 8 m/s at hub height is taken as reference, i.e. specific energy cost equals 1,00 or 100%.

## Approach 2:
## Turbine design for series production

Assumption:
Cost reduction through series production and economy of scales

⇒ Type Class concept instead of site-specific design
  ⇒ (most) turbines are over-designed at a given site
⇒ manufacturer-specific product concept / platform concept

# IEC 61400-1 ed.3 : Wind Turbine Generator Systems – Safety Requirements

- IEC = International Electro-technical Commission
- International standard for wind turbines with > 40 $m^2$ swept area, relevant worldwide with exception of Germany and Denmark, issued as EN Standard by CENELEC
- Part 1 („-1“)
  - safety requirements, load cases, structural integrity for entire wind turbine
  - no component design
- 3rd edition 2005

- Offshore edition 61400-3 (extension of 61400-1)



# Type class concept according to IEC 61400-1 ed.3

IEC: Type classes I – III and S

- $V_{ref}$ : mean (10 min.) wind speed with 50 years recurrence period
- $V_{ave}$: Annual average wind speed = 0.2 * $V_{ref}$
- $I_{ref}$ : (Mean) Turbulence intensity at 15 m/s (class A, B or C)

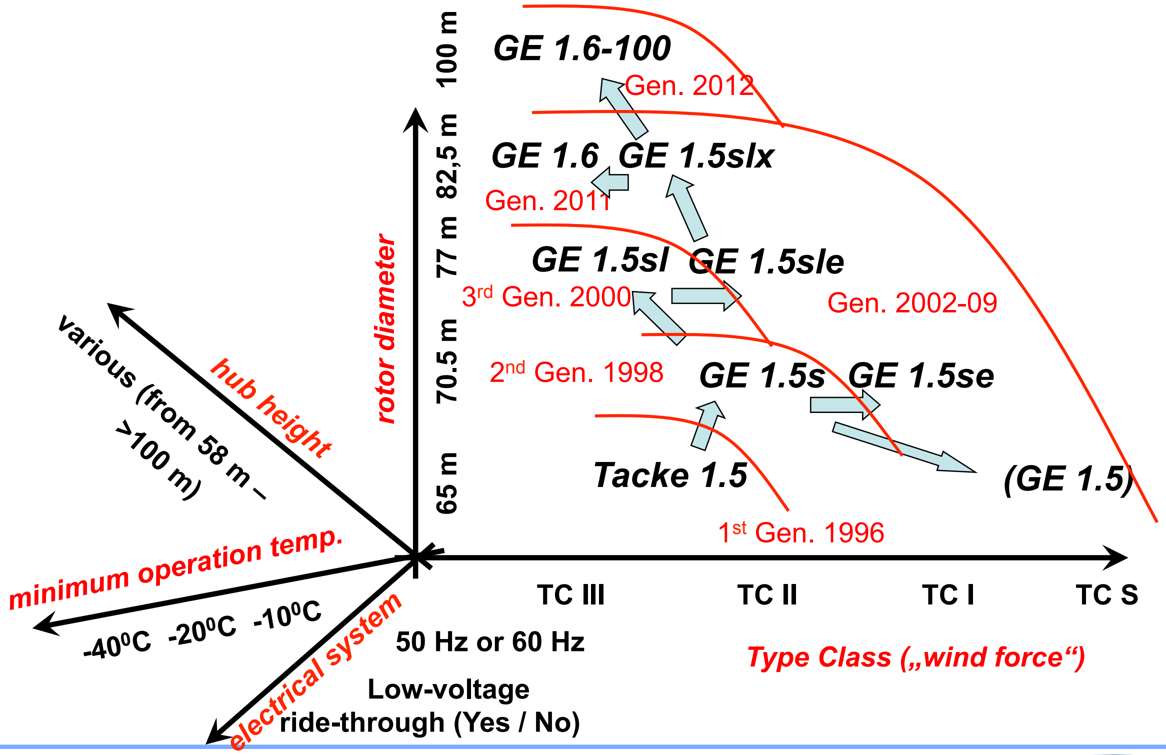
| Wind turbine class | | I | II | III | S |
|---|---|---|---|---|---|
| $V_{ref}$ | (m/s) | 50 | 42,5 | 37,5 | Values specified by the designer |
| A | $I_{ref}$ (-) | | 0,16 | | |
| B | $I_{ref}$ (-) | | 0,14 | | |
| C | $I_{ref}$ (-) | | 0,12 | | |

Concept of type classes enables:

- simplified building permits
- product standardisation and series production
- short delivery time

## Series production and international customization

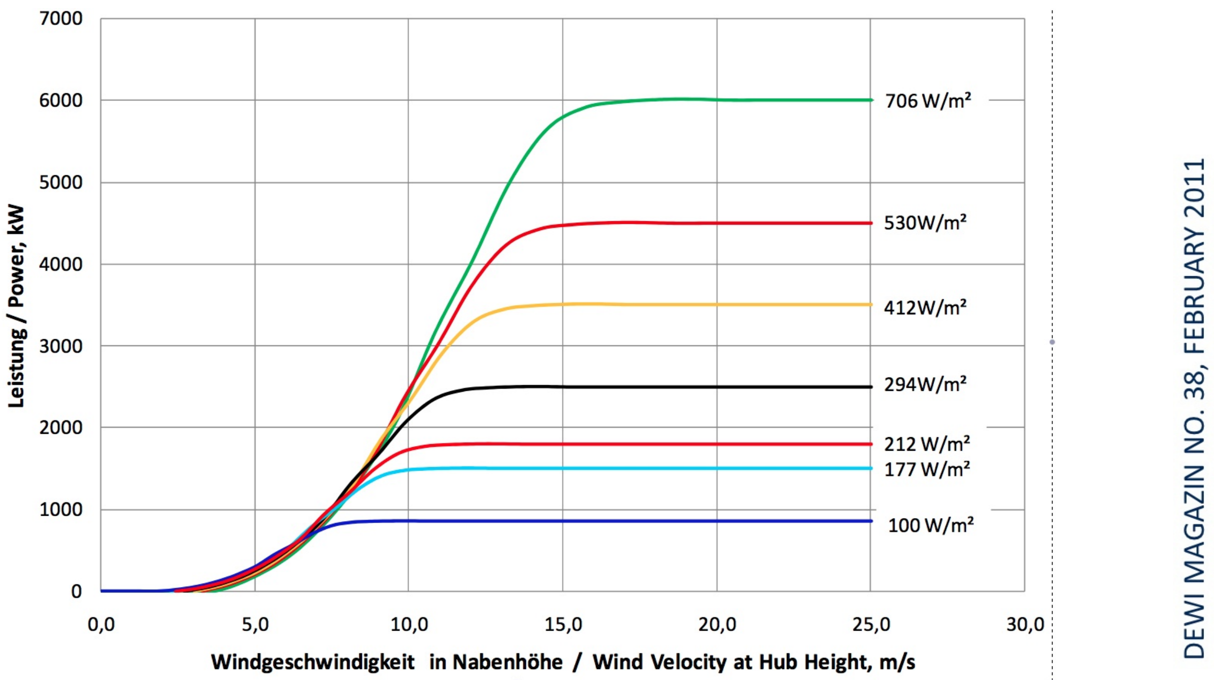
### (Example of multiple generations of GE 1.5 MW platform)

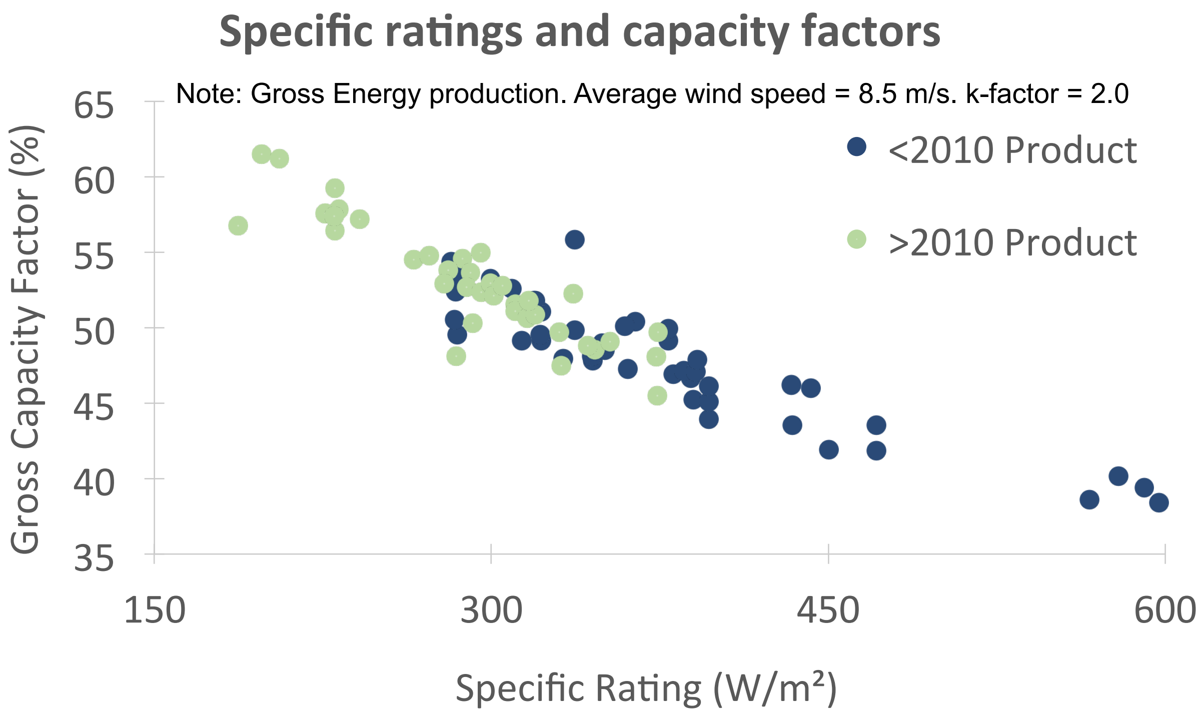





## Theoretical power curves for a typical wind turbine Ø 104 m:

### => What is the optimum rated power (or specific rating)?

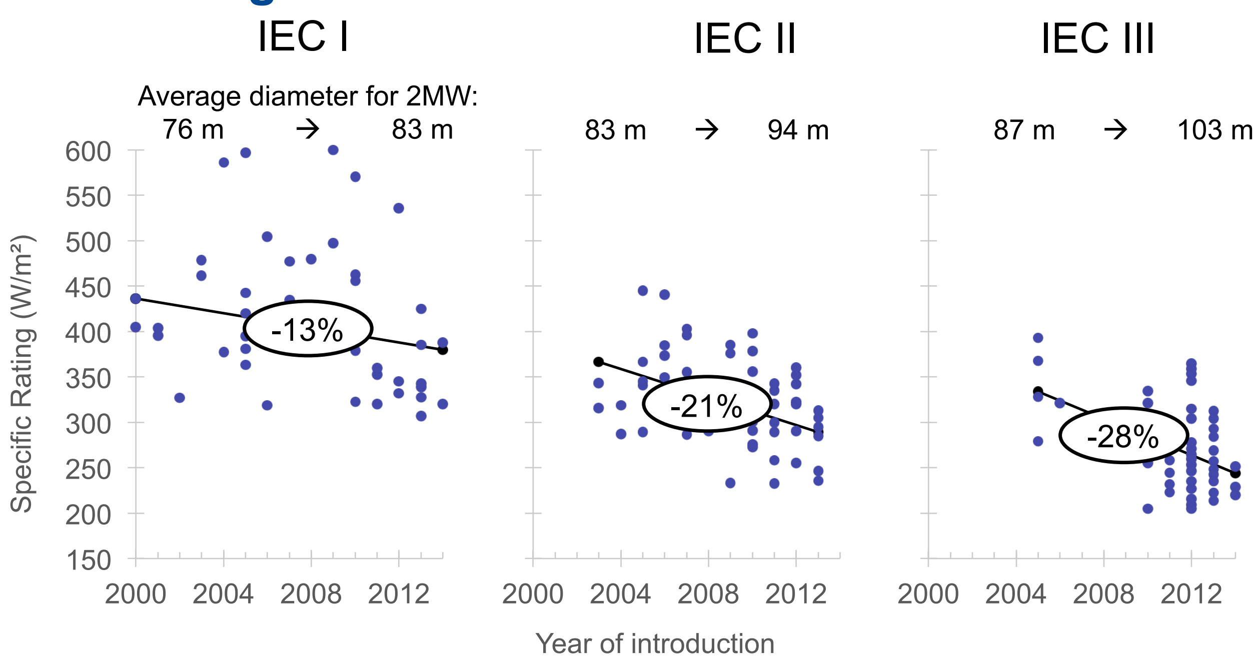





Source: MAKE Engineering, Global Wind Turbine Trends 2013, Dec. 2013

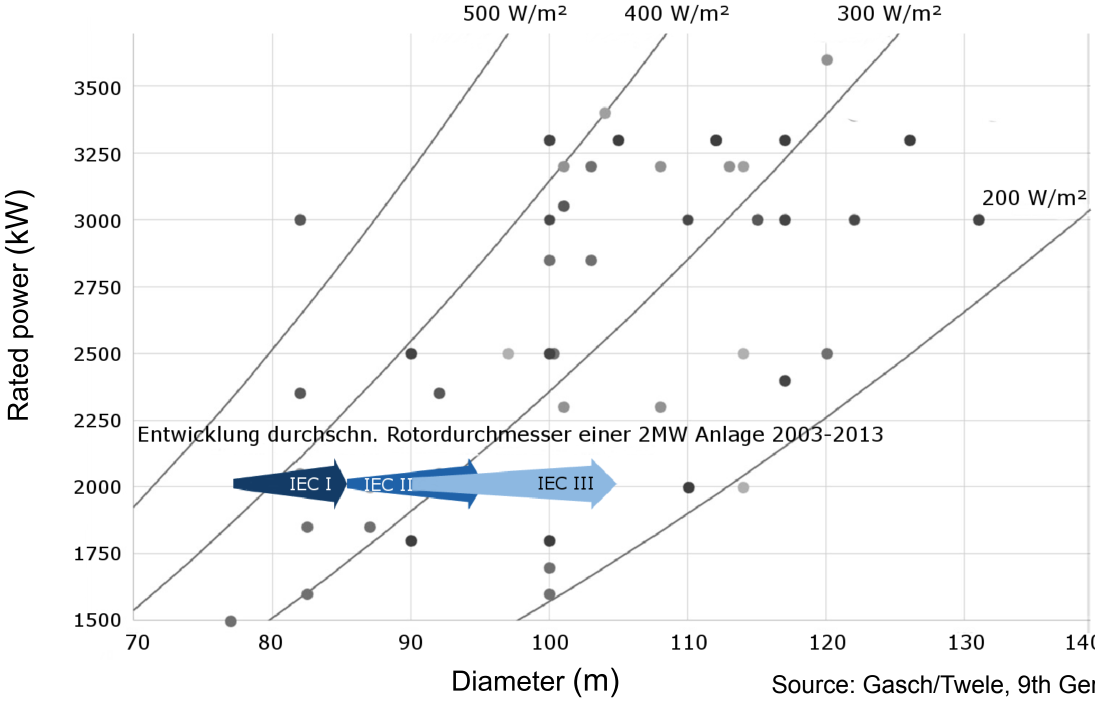


# Trend of increasing rotor diameter in different market segments




Source: MAKE Engineering, Global Wind Turbine Trends 2013, Dec. 2013

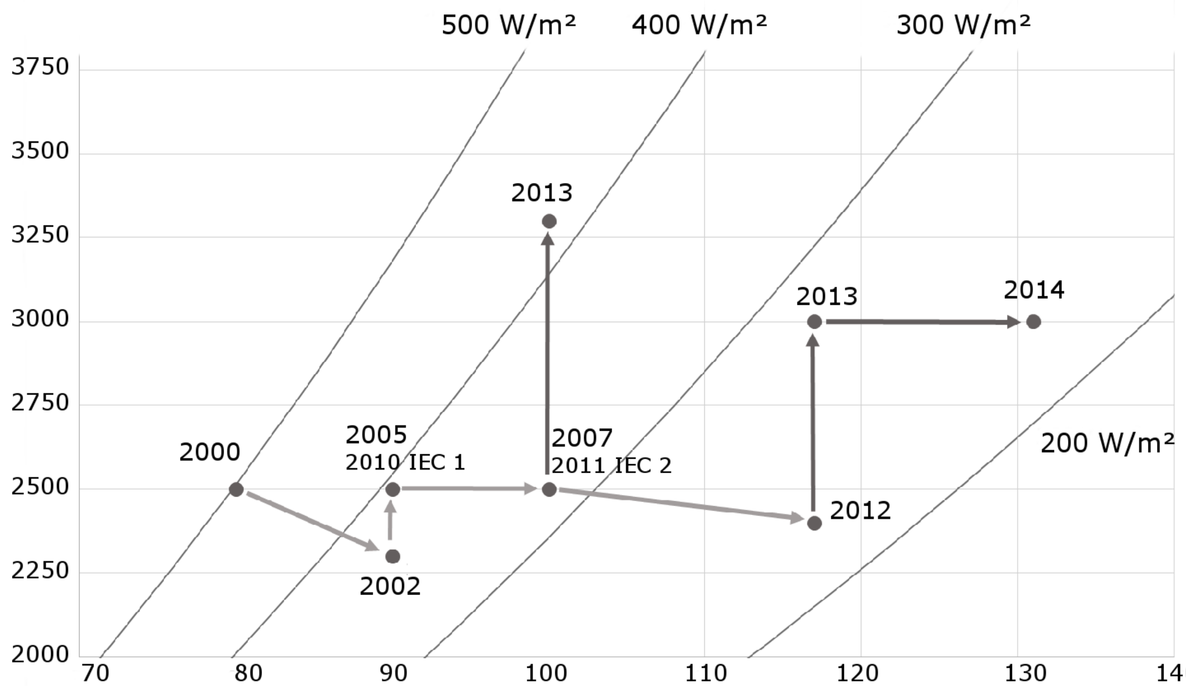
# Trend of increasing rotor diameter: Example development of Senvion 2 MW platform




Source: Gasch/Twele, 9th German ed.



# Trend of increasing rotor diameter: Example development of Norex 2.x-3 MW platform




Source: Gasch/Twele, 9th German ed.

## Best turbine in class by segment [MAKE]

| | IEC I | IEC II | IEC III |
|---|---|---|---|
| **< 2.5 MW** | Enercon E92-2.35<br>Vestas V90-2.0 | Enercon E115-2.5<br>Vestas V100-1.6 | Vestas V110-2.0<br>GE 1.7-100 |
| **2.4-3.5 MW** | Vestas V112-3.3<br>Siemens SWT 3.0-108 | Alstom<br>ECO 122-2.7<br>Enercon E115-2.5 | Nordex N131-3.0<br>GE 2.5-120 |
| **> 3.5 MW** | AREVA M8000-180<br>Vestas V164-7/8 | Senvion<br>6M-152 | |



## Approach 3: Turbine design for high penetration of renewable power

Basic idea:

Renewable power dource are hard predictable. Other parameter besides the levelized cost of energy may influence the economic benefits of a wind turbine.

E.g. wind turbine design with a low specific rate show:

$\Longrightarrow$ Steady power production over longer time $\Rightarrow$
**more efficient grid connection**

$\Longrightarrow$ Higher capacity factor $\Rightarrow$
**lower risk not to honor the agreed AEP**

$\Longrightarrow$ Smaller difference between rated and average power $\Rightarrow$
**better utilization, less maintenance**

Overall monetary advantages

## Summary

- The share of installed wind power capacity is continuously growing up world-wide . This boots technical innovations and leads to a steep growth of largest rotor diameter and rated power.

- Wind turbine design is a step process which includes
  - market analysis
  - aero-elastic simulations (load cases defined by standard)
  - ultimate loads  and fatigue analysis
  - prototype test
  - certification

- Wind turbine design can be driven by
  - economical optimization (cost of energy)
  - industrialization (optimization of costs given by serial production)
  - political laws which regulate the energy market and promote renewable energy