Renewable Energy Resources (RER)

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Wind Energy

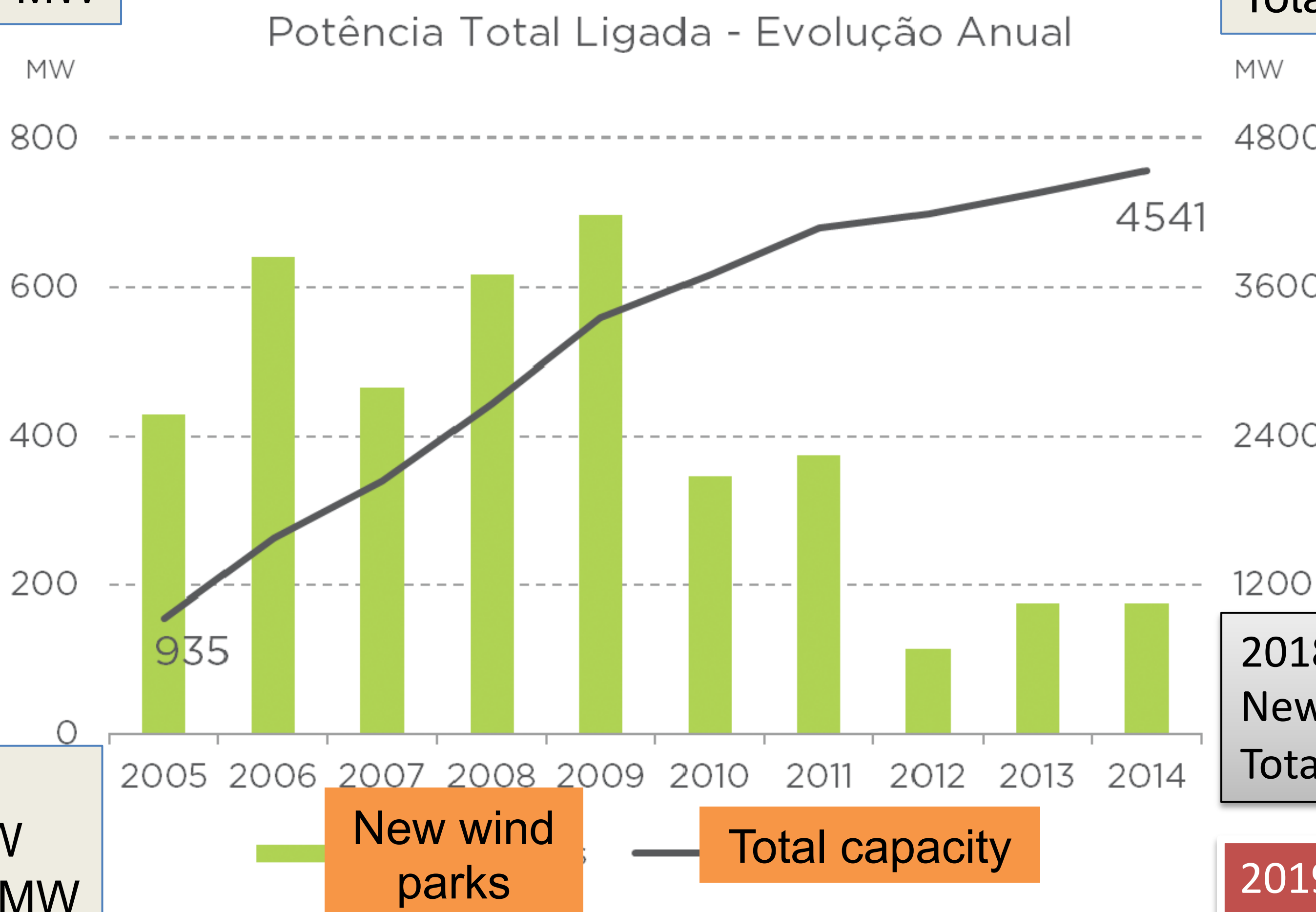
Chapter 4

WIND FACTS AND FIGURES

Wind Power in Portugal

2016
New: 244 MW
Total: 5070 MW

2015
New: 285 MW
Total: 4826 MW



2018
New: 51 MW
Total: 5150 MW

2017
New: 29 MW
Total: 5099 MW

2019
New: 58 MW
Total: 5208 MW

Source: REN

Wind Energy in the World

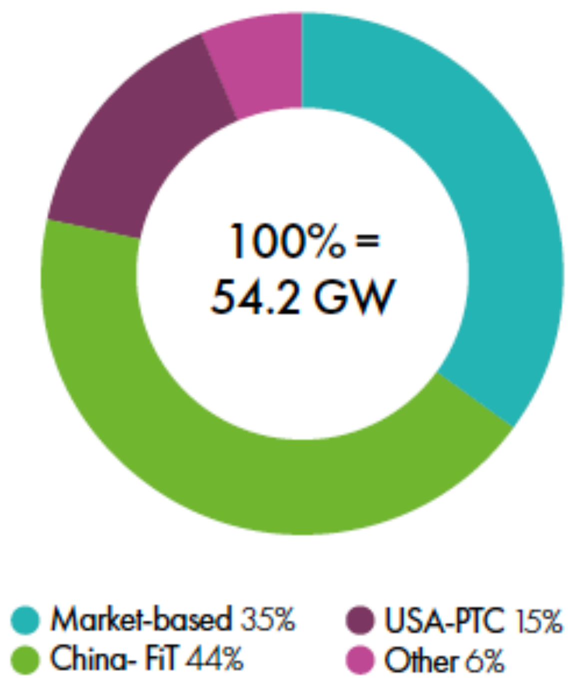
Top markets 2019

Detailed data sheet available in GWEC's member only area. For definition of region, see Methodology and Definitions in the Appendix
Source: GWEC Market Intelligence, March 2020

Source: GWEC

Wind Support Mechanisms

New capacity 2019 by support mechanism
(%, onshore)



FiT – Feed in Tariff
PTC – Production Tax Credit

Source: GWEC

Wind LCOE

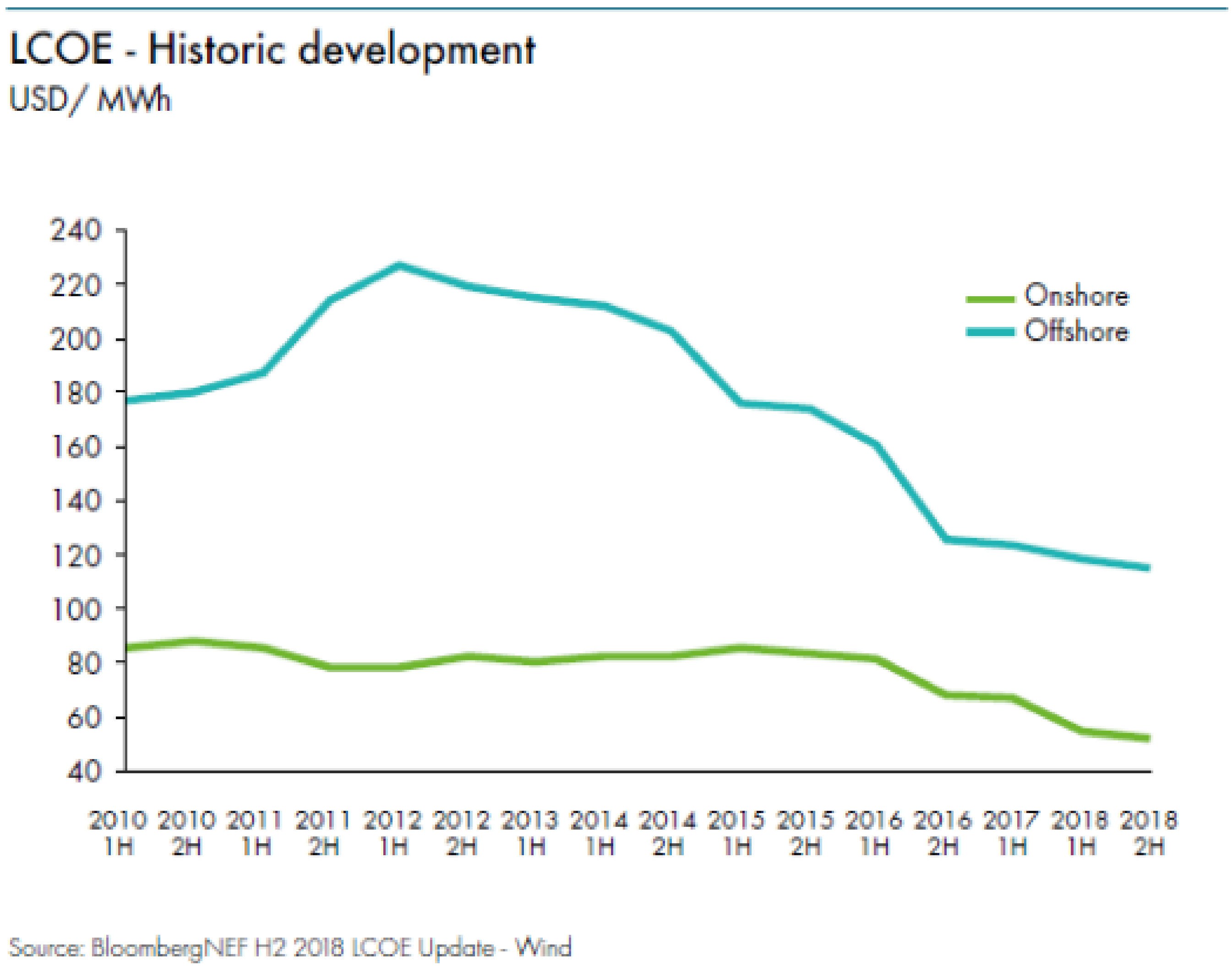
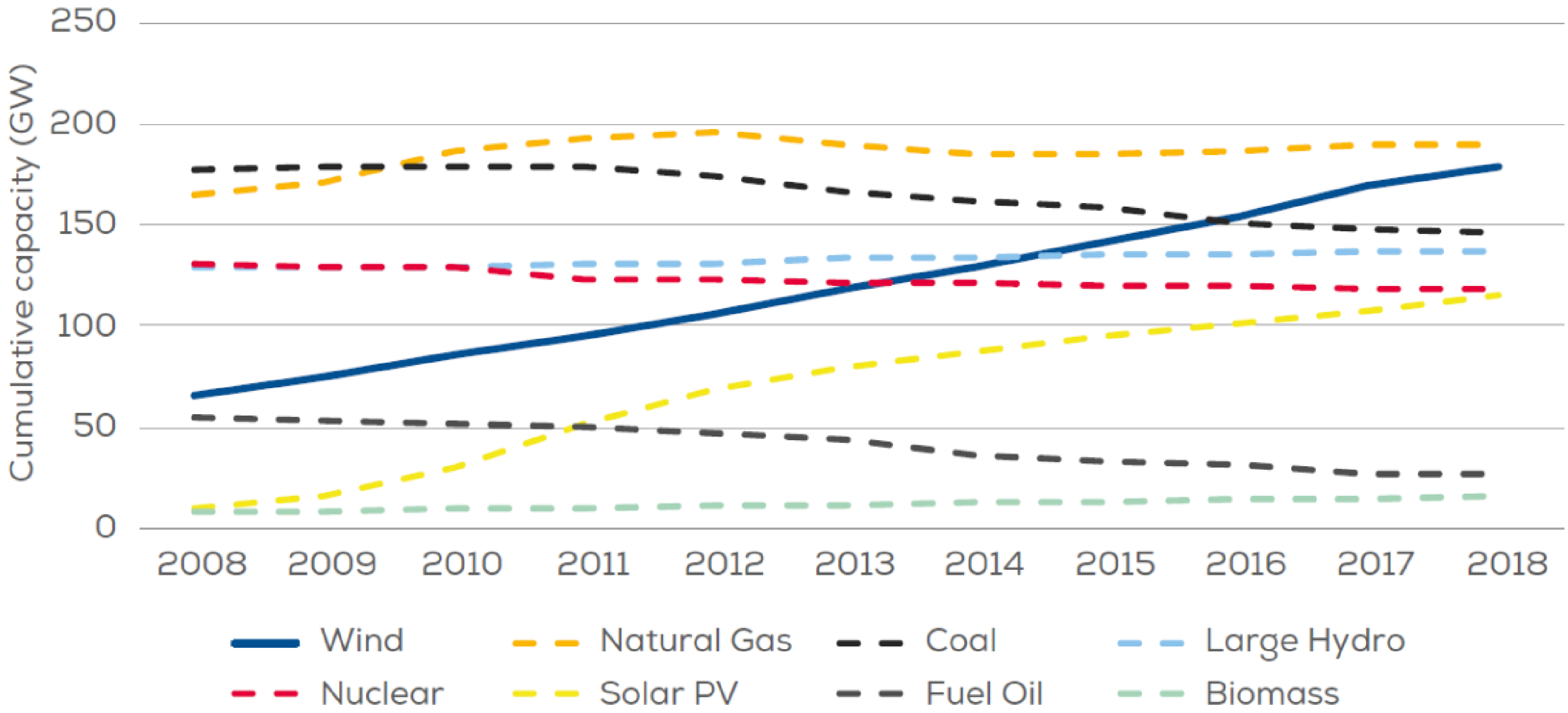

LCOE - Historic development
USD/ MWh
240
220
200
180
160
140
120
100
80
60
40
Onshore
Offshore
2010 1H
2010 2H
2011 1H
2011 2H
2012 1H
2012 2H
2013 1H
2014 1H
2014 2H
2015 1H
2015 2H
2016 1H
2016 2H
2017 1H
2018 1H
2018 2H
Source: BloombergNEF H2 2018 LCOE Update - Wind

FIGURE 1

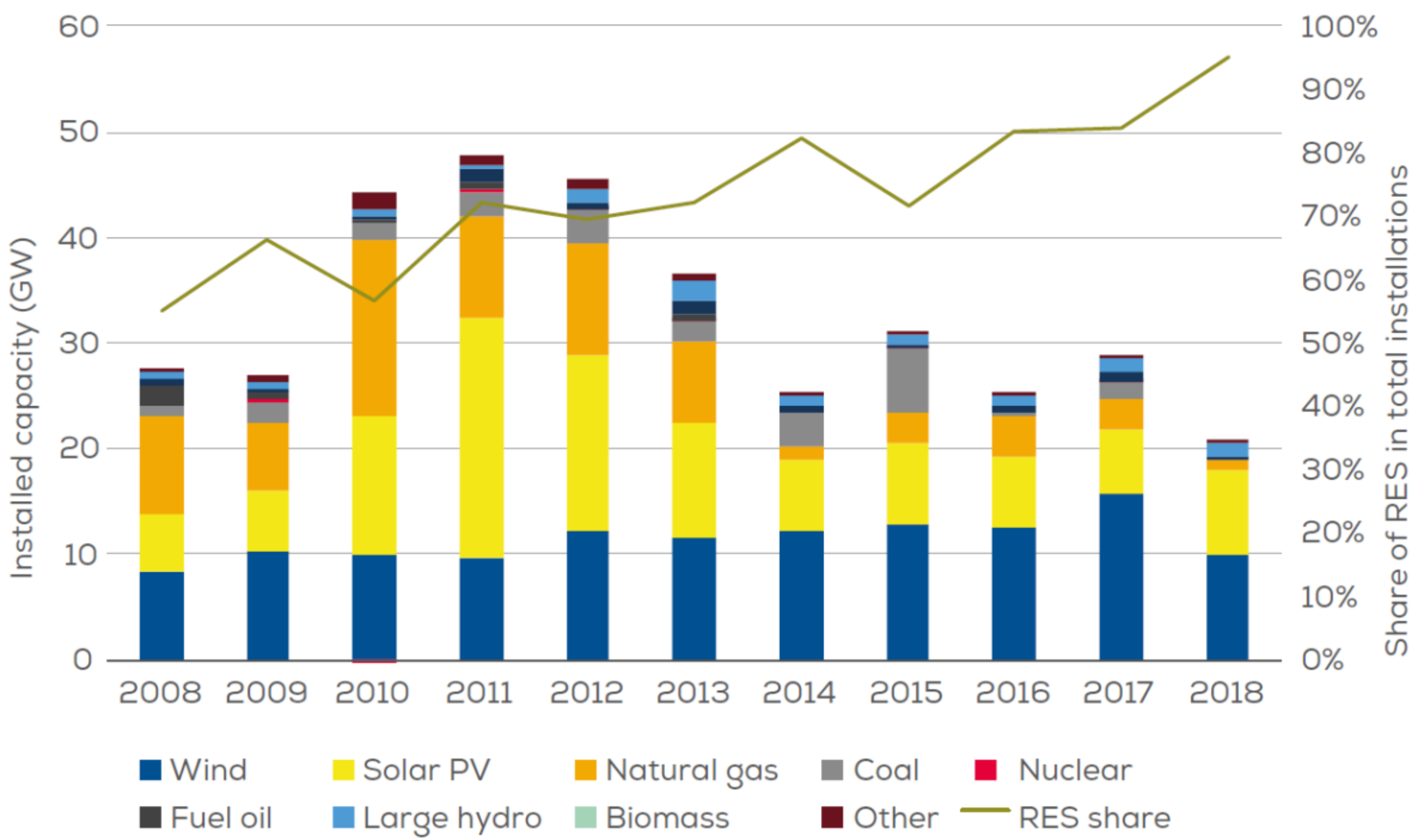
Total power generation capacity in the European Union 2008-2018



Source: WindEurope

FIGURE 15

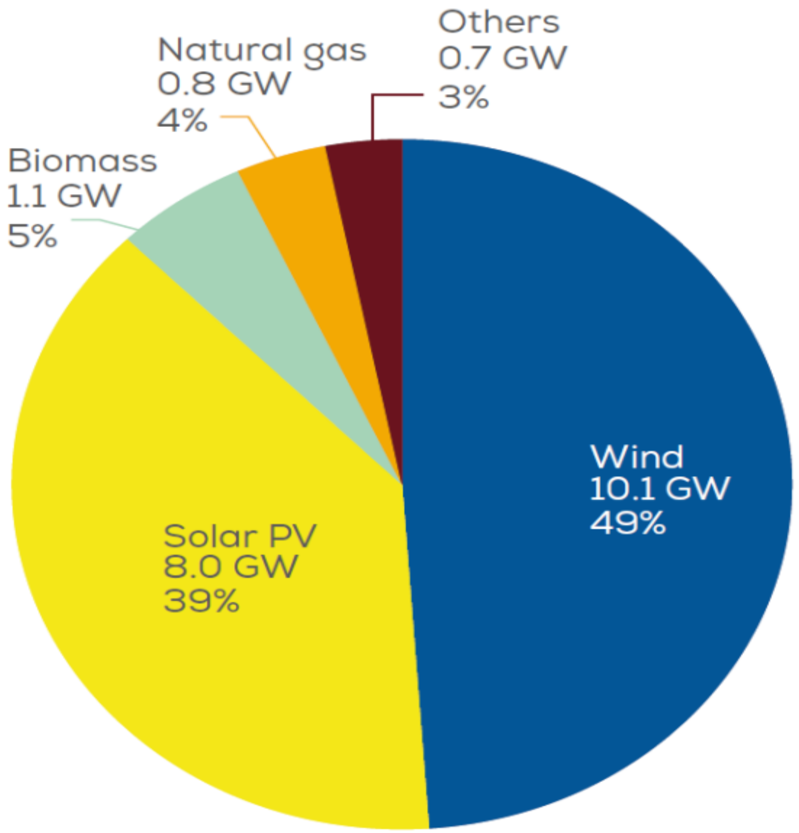
Annual installed capacity and renewable share in EU-28



Source: Wind Europe

FIGURE 13

Share of new installed capacity in the EU-28



Source: Platts, SolarPowerEurope, WindEurope

WIND IS NOW THE

2nd LARGEST POWER GENERATING CAPACITY IN THE EU

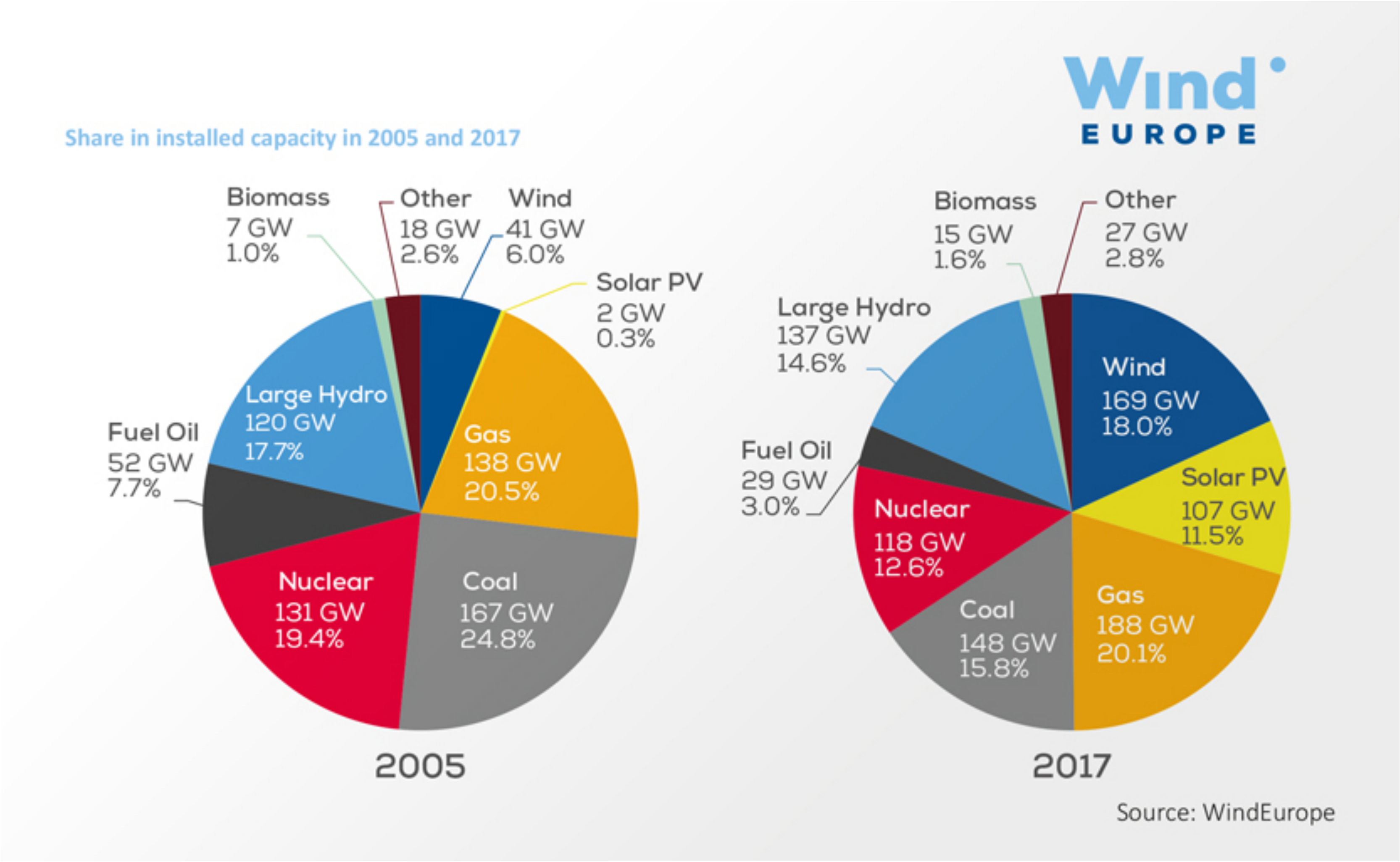
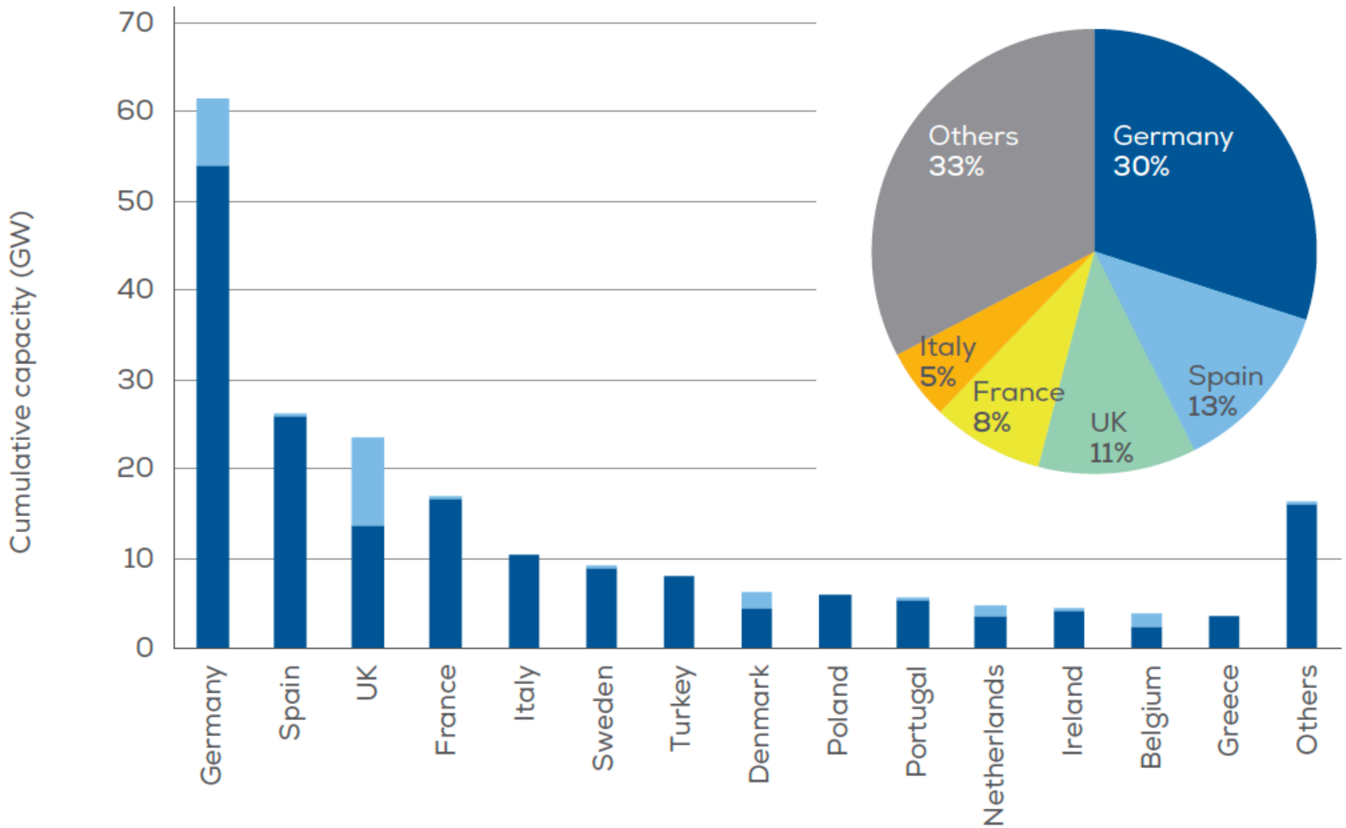


FIGURE 6

Total installed wind power capacity by country

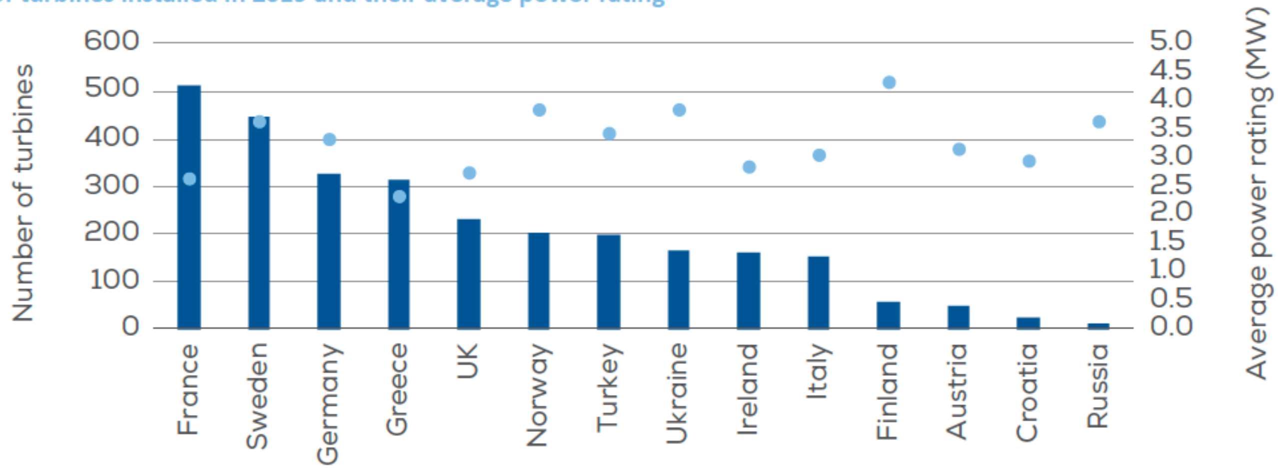


Offshore	7	-	10	-	-	-	-	2	-	-	1	-	2	-	-
Onshore	54	26	14	17	11	9	8	4	6	5	3	4	2	4	16
Total	**61**	**26**	**24**	**17**	**11**	**9**	**8**	**6**	**6**	**5**	**4**	**4**	**4**	**4**	**16**

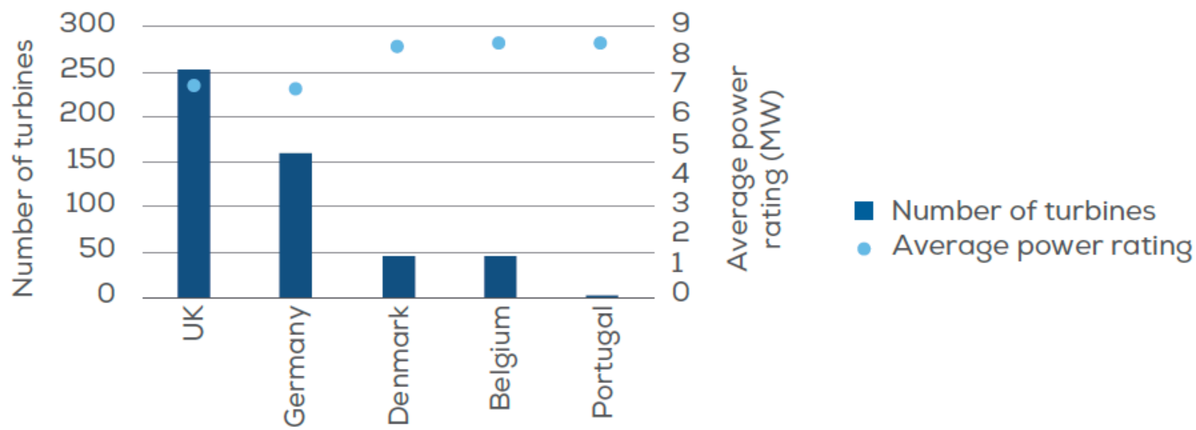
Source: WindEurope

FIGURE 10

Number of turbines installed in 2019 and their average power rating



	France	Sweden	Germany	Greece	UK	Norway	Turkey	Ukraine	Ireland	Italy	Finland	Austria	Croatia	Russia
Number of turbines	511	447	325	314	230	204	200	166	163	154	56	49	24	14
Average power rating	2.6	3.6	3.3	2.3	2.7	3.8	3.4	3.8	2.8	3	4.3	3.1	2.9	3.6



	UK	Germany	Denmark	Belgium	Portugal
Number of turbines	252	160	45	44	1
Average power rating	7	6.9	8.3	8.4	8.4

Source: WindEurope

FIGURE 4

Distribution of the new wind installations in Europe

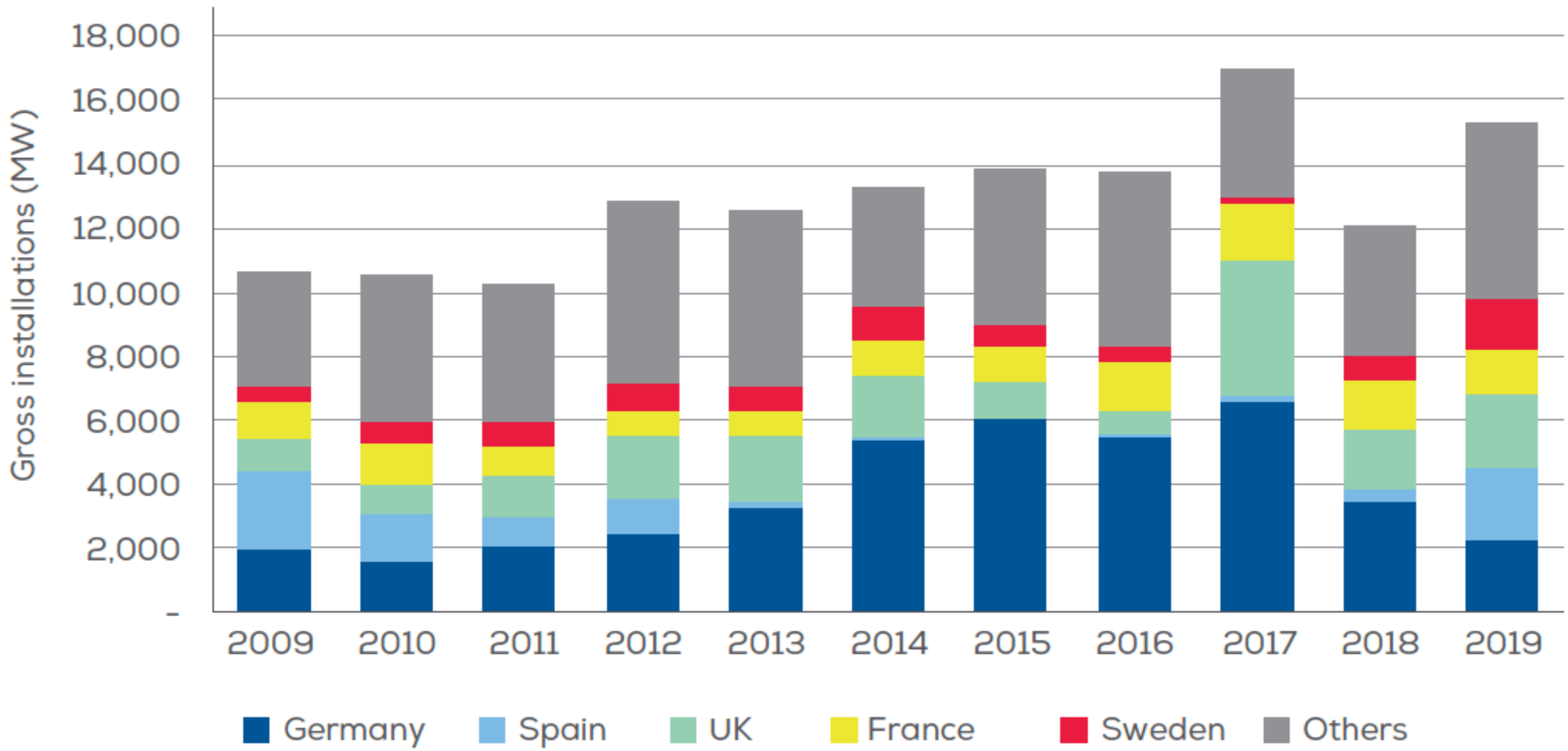
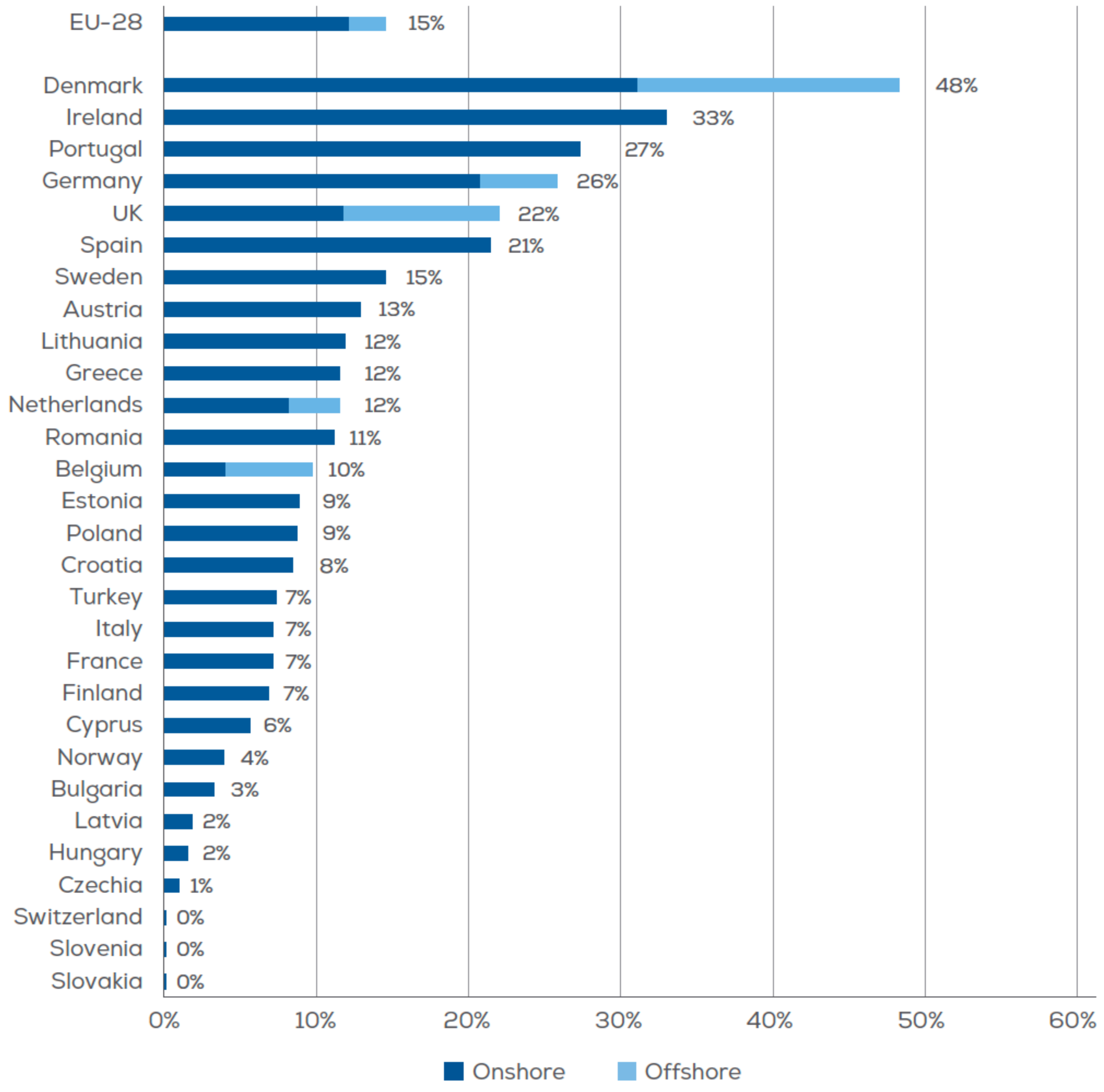


FIGURE 8

Percentage of the electricity demand covered by wind in 2019[11]



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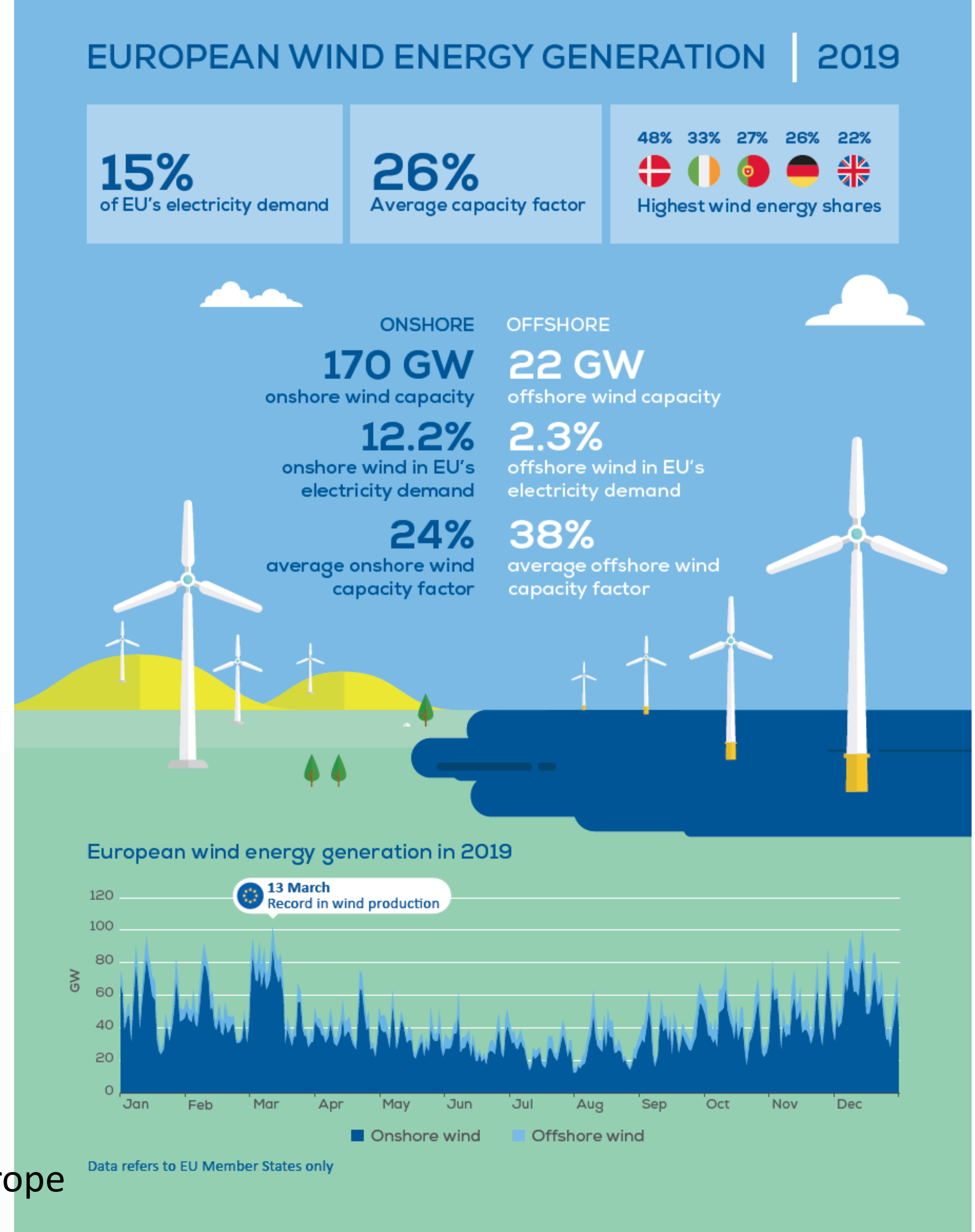
Source: WindEurope

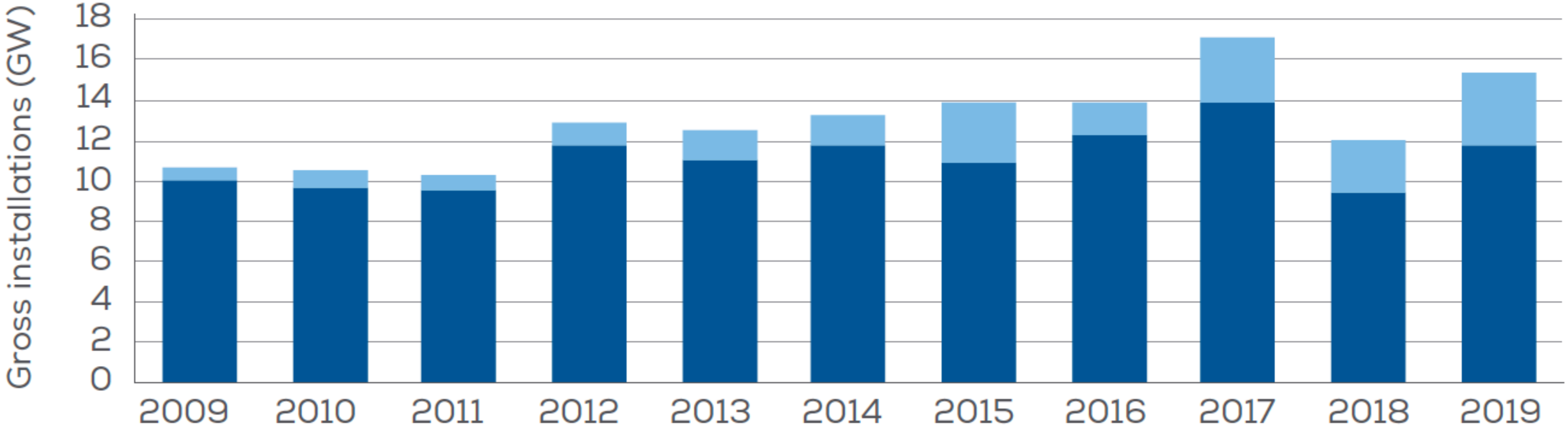


Source: Wind Europe

OFFSHORE WIND POWER

FIGURE 2

New annual onshore and offshore wind installations in Europe

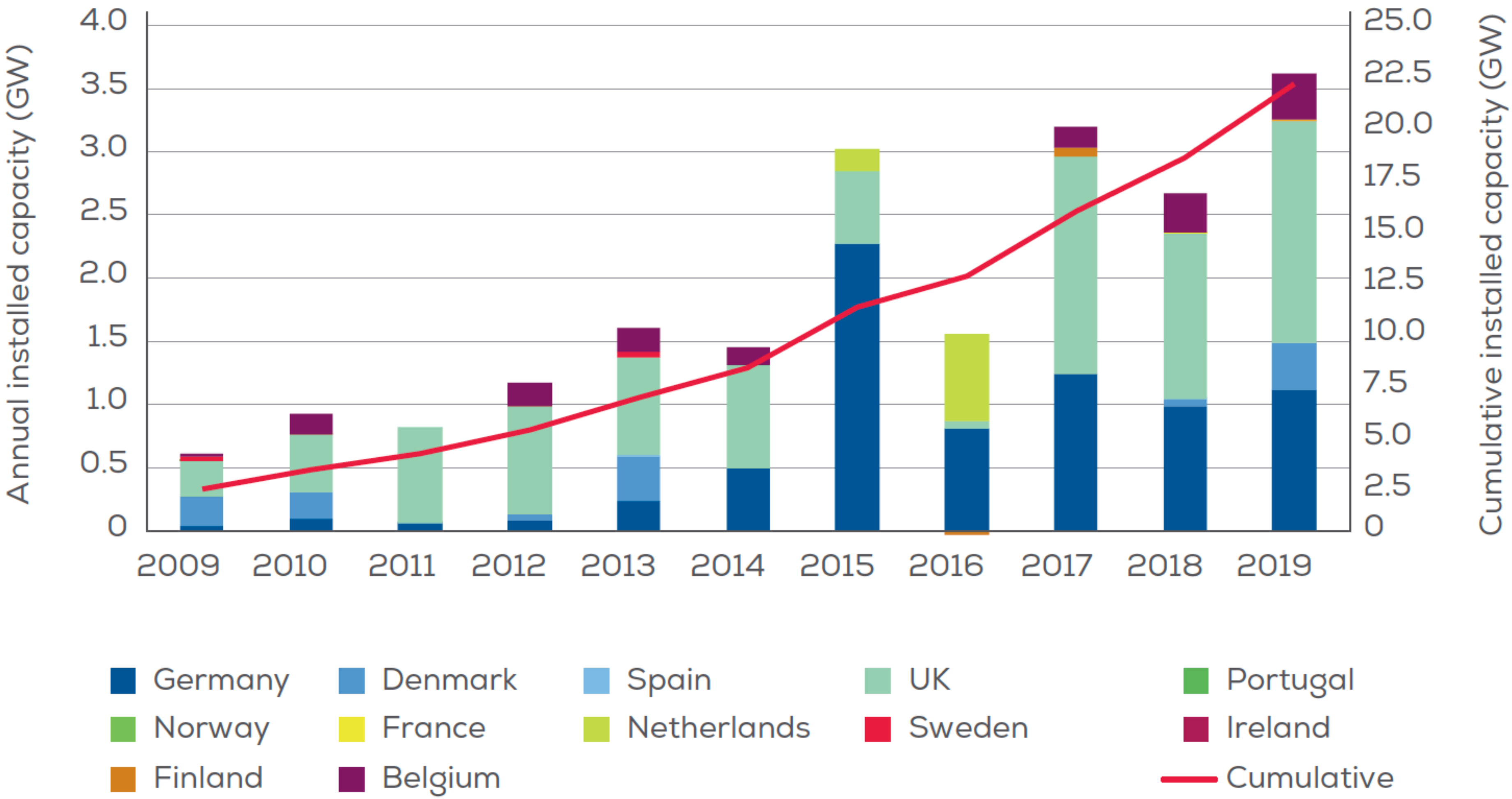


	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Offshore	0.6	0.9	0.8	1.2	1.5	1.5	3.0	1.6	3.2	2.7	3.6
Onshore	10.0	9.6	9.5	11.7	11.0	11.7	10.9	12.3	13.9	9.4	11.7
Total	**10.7**	**10.5**	**10.3**	**12.9**	**12.5**	**13.3**	**13.9**	**13.8**	**17.1**	**12.1**	**15.4**

Source: WindEurope

FIGURE A

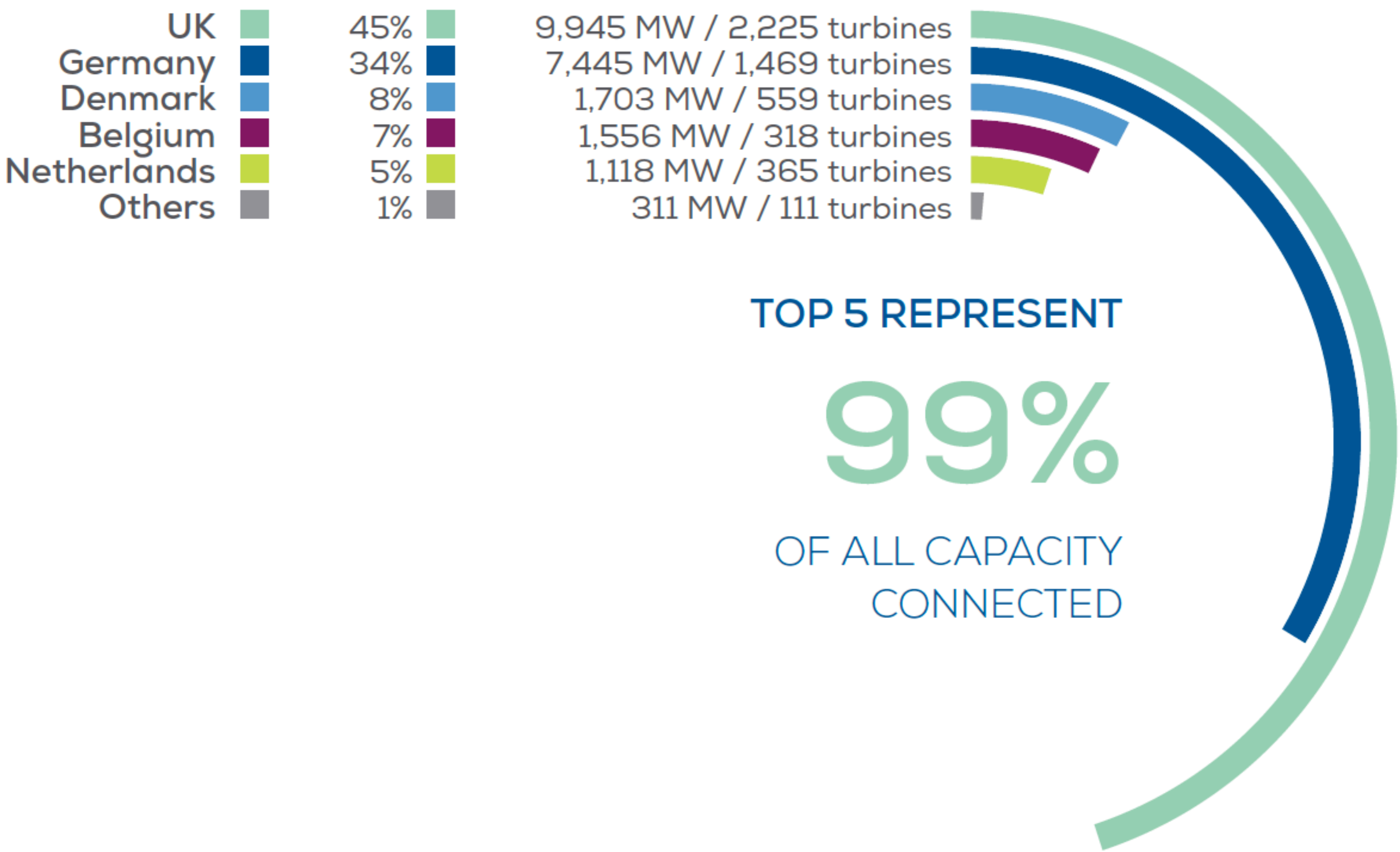
Annual offshore wind installations by country (left axis) and cumulative capacity (right axis) (GW)



Source: WindEurope

FIGURE 3

Cumulative installed capacity (MW) and number of turbines by country



Source: WindEurope

FIGURE 5

Yearly average of newly installed offshore wind turbine rated capacity (MW)

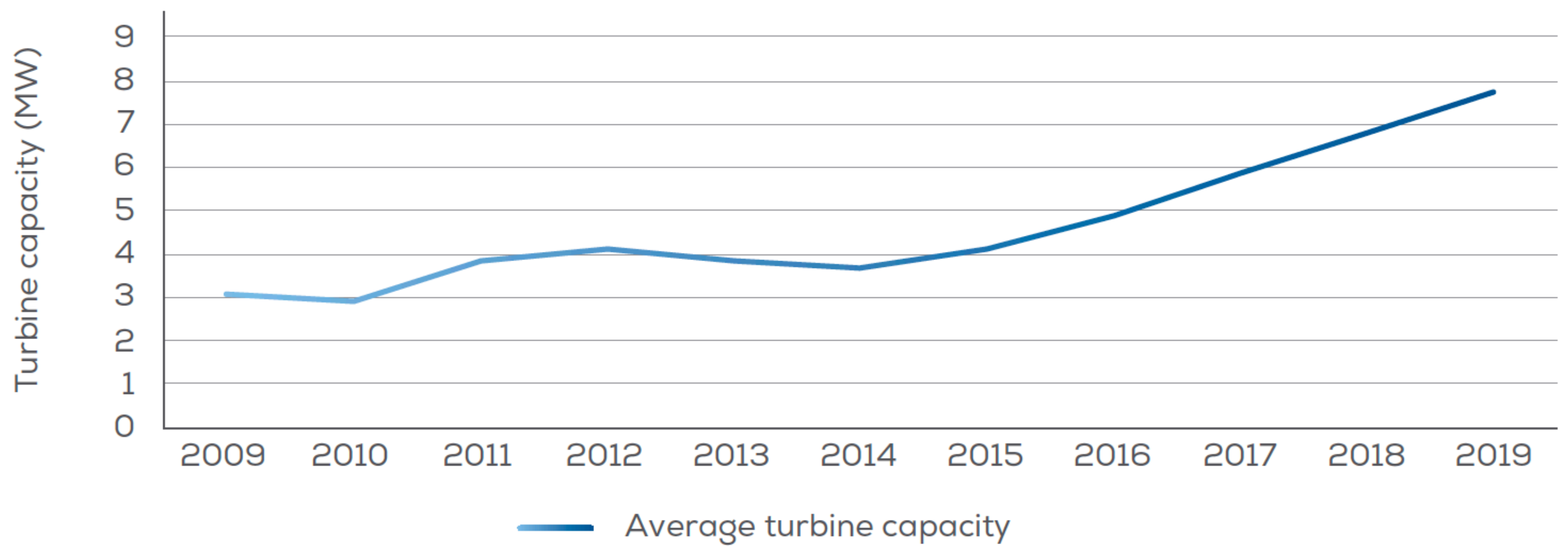
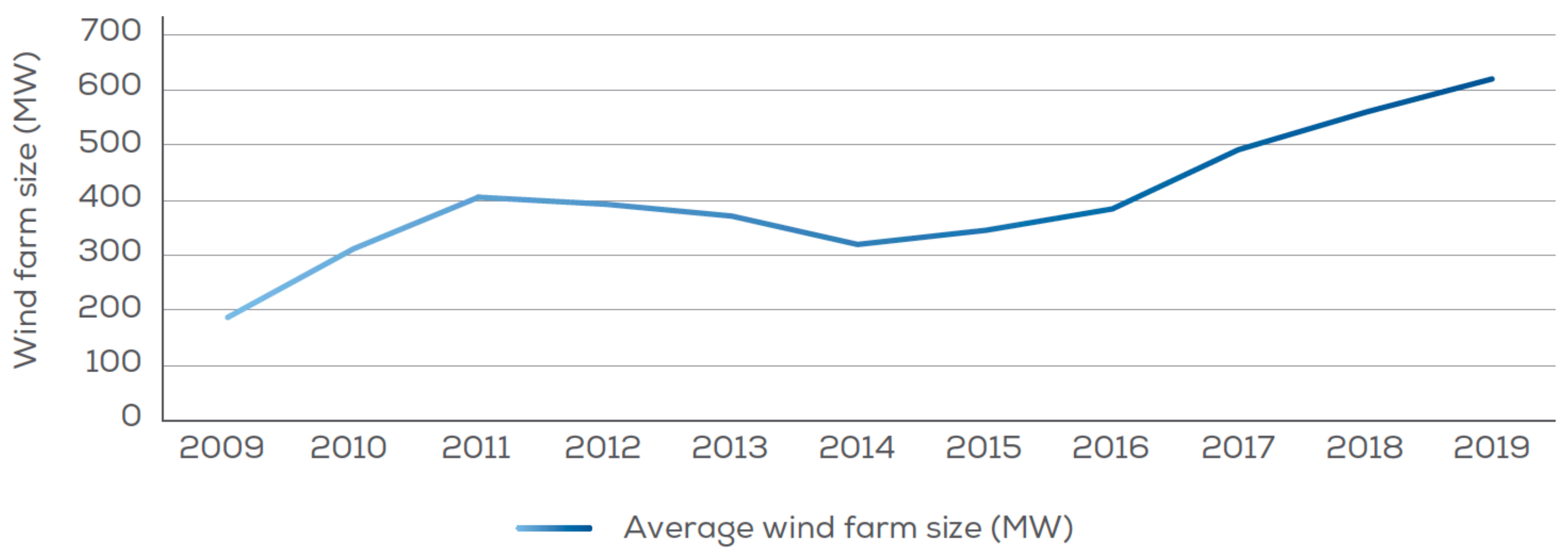


FIGURE 6

Average size of commercial offshore wind farm projects in the year (MW)



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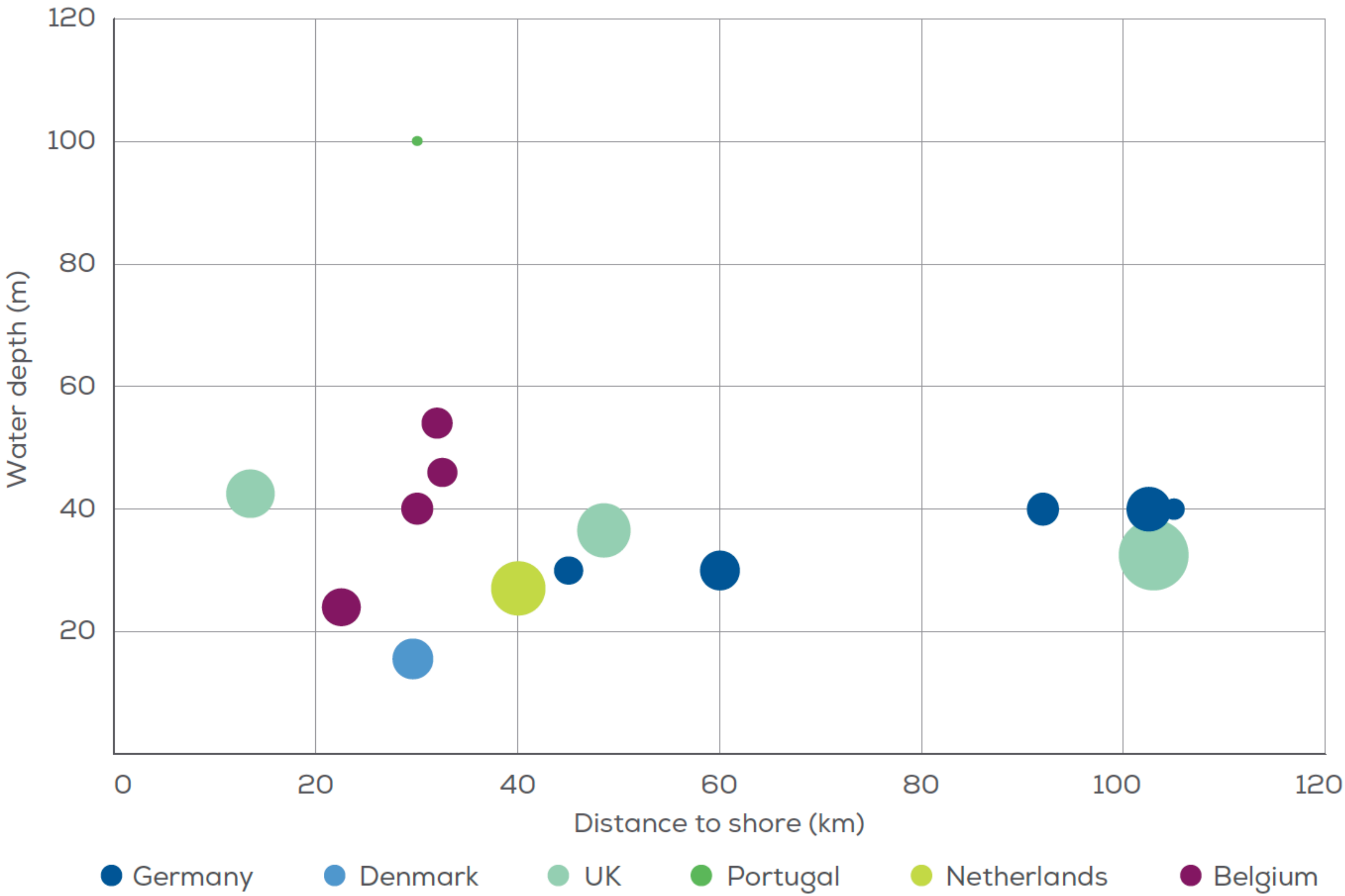
Source: WindEurope

FIGURE 8

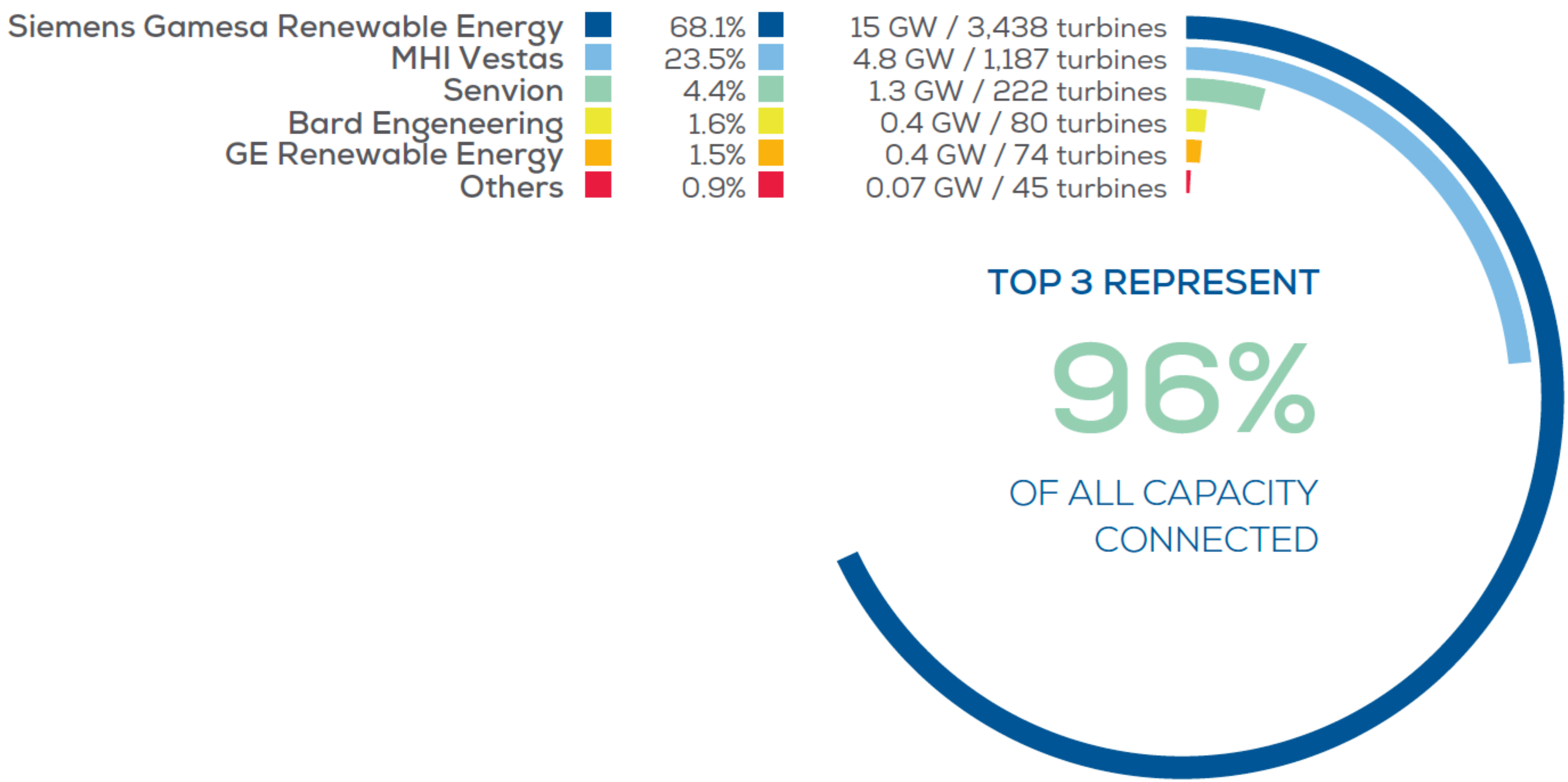
Average water depth and distance to shore of offshore wind farms under construction during 2019. The size of the bubble indicates the capacity of the site



Source: WindEurope

FIGURE 12

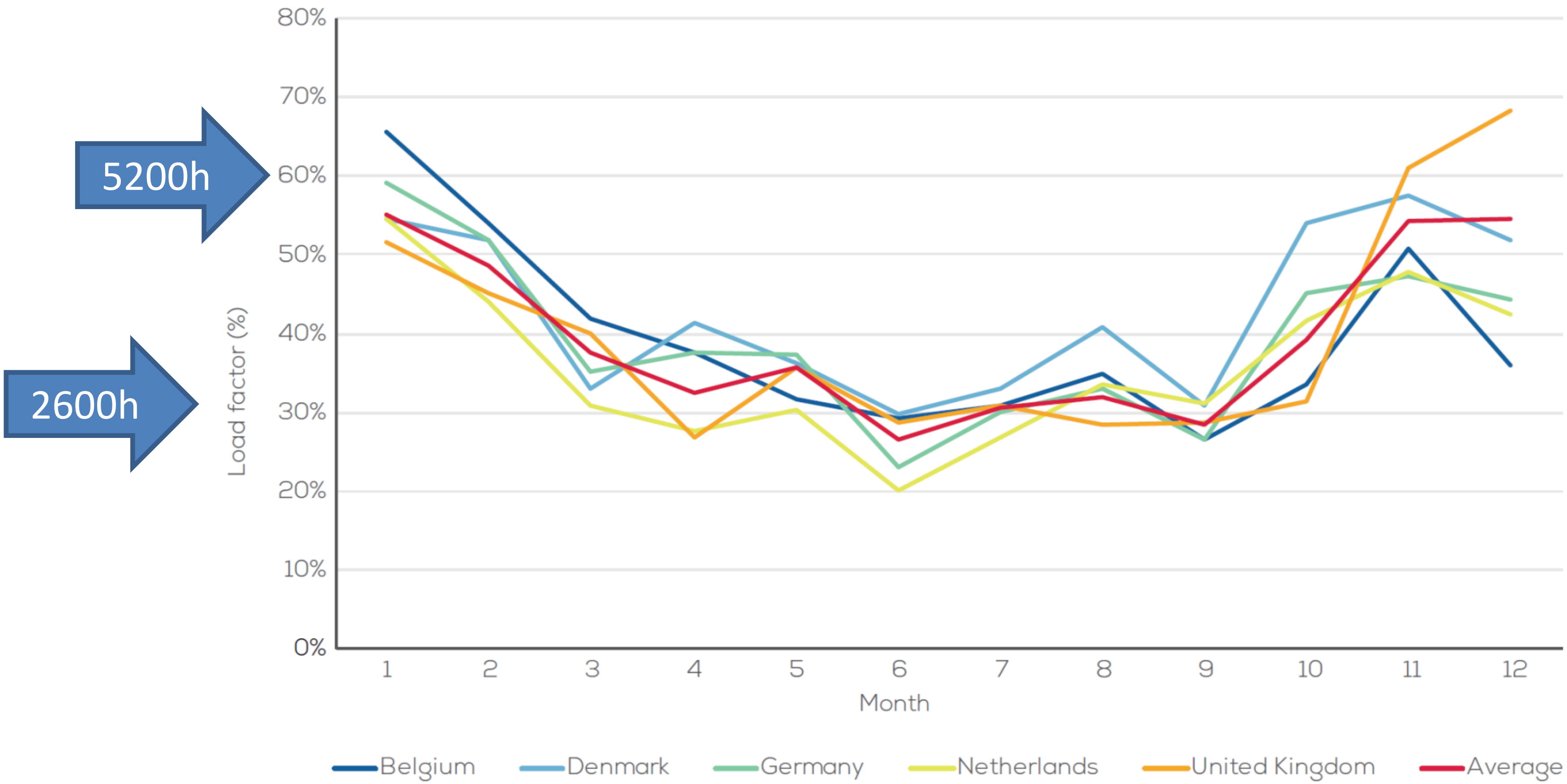
Wind turbine manufacturers' share at the end of 2019



Source: WindEurope

FIGURE 13

Monthly national load factors of offshore wind in 2016 (percent)[7]



Average in offshore Europe:
37% = 3200 h

Source: WindEurope

Cumulative offshore installations

- 5,047 offshore turbines are now installed, and grid connected, making a cumulative total of 22,072 MW.
- Including sites with partial grid-connected turbines, there are now 110 offshore wind farms in 12 European countries.
- The UK has the largest amount of offshore wind capacity in Europe with 45% of all installations. Second is Germany with 34%, followed by Denmark (8%).

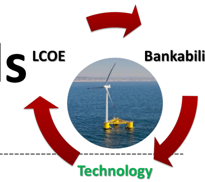
Offshore – Example in Portugal

- Aguçadoura – Póvoa do Varzim
  - WindFloat, 2 MW
  - 6 km distance
  - 60 m depth
  - EDP, Principle Power, A. Silva Matos e Vestas
  - 20 M€
  - Decommissioned in 2017

WindFloat Atlantic

- Phase II – 3 WTG of 8.4 MW, Total of 25 MW
- Floating structure with 30 m height and 50 m between each column
- WTG rotor at 164 m height

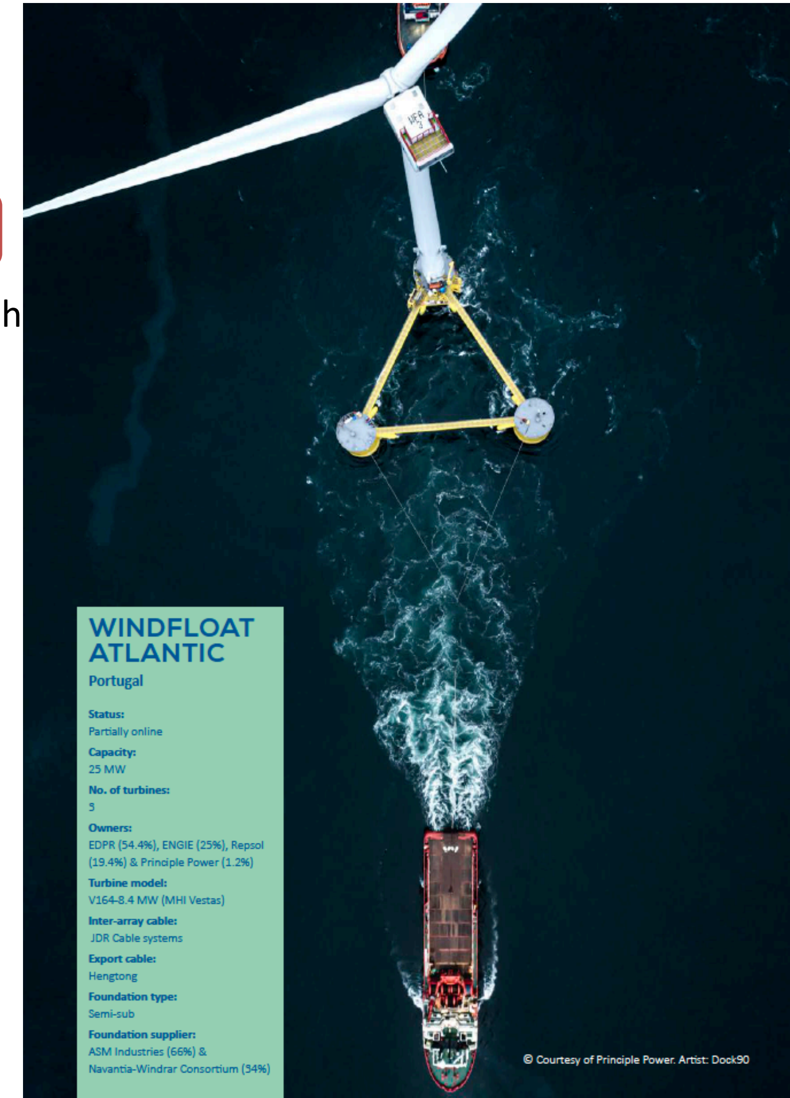
The WindFloat Atlantic is the next stage of development and intends to demonstrate the pre-commercial phase of the technology



- ***Total capacity:*** **25MW capacity**, (3 units equipped with MHI-Vestas V164)
- ***Total investment:*** **~125M€** (partly funded by the EC)

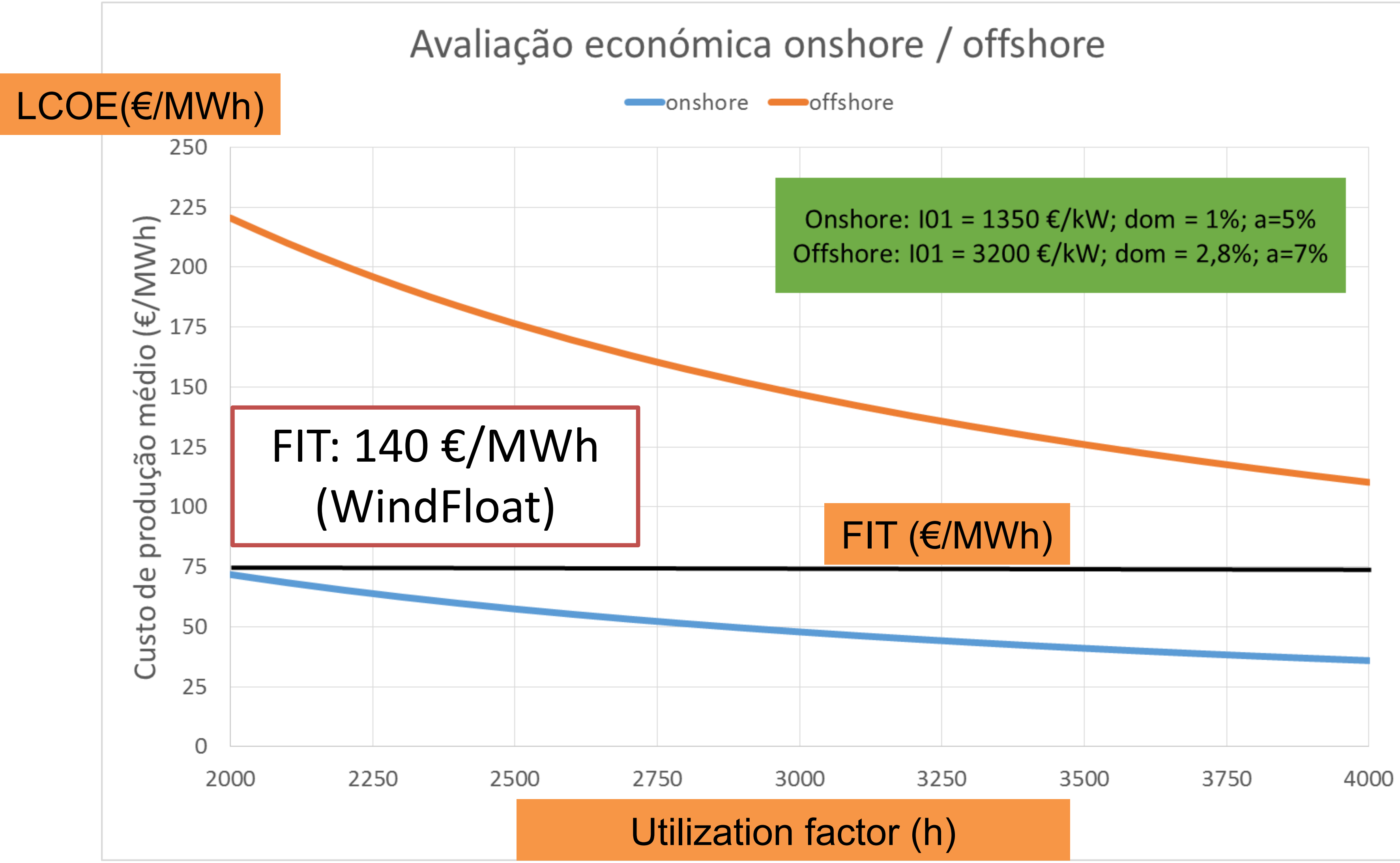
NER 300 and FiT | **Equity** | **Project Finance**

- ***Location:*** 20 km off the coast of **Viana do Castelo**, in water depth of 85-100m, in an area of sand and sediments, suitable for mooring
- ***Interconnection:*** to be constructed by REN, allowing a **direct connection at 60kV** with no onshore of offshore substation
- ***Construction:*** several **shipyards** options available close to final location. **Turbine installation quayside**
- ***Floating structure certification:*** designed for **25 years**, certified throughout design, construction and installation by **ABS,** an independent party
- ***Key Dates:***
  - FID: Q2-2017
  - Start Fabrication: Q3 2017



Source: EDP-Inovação

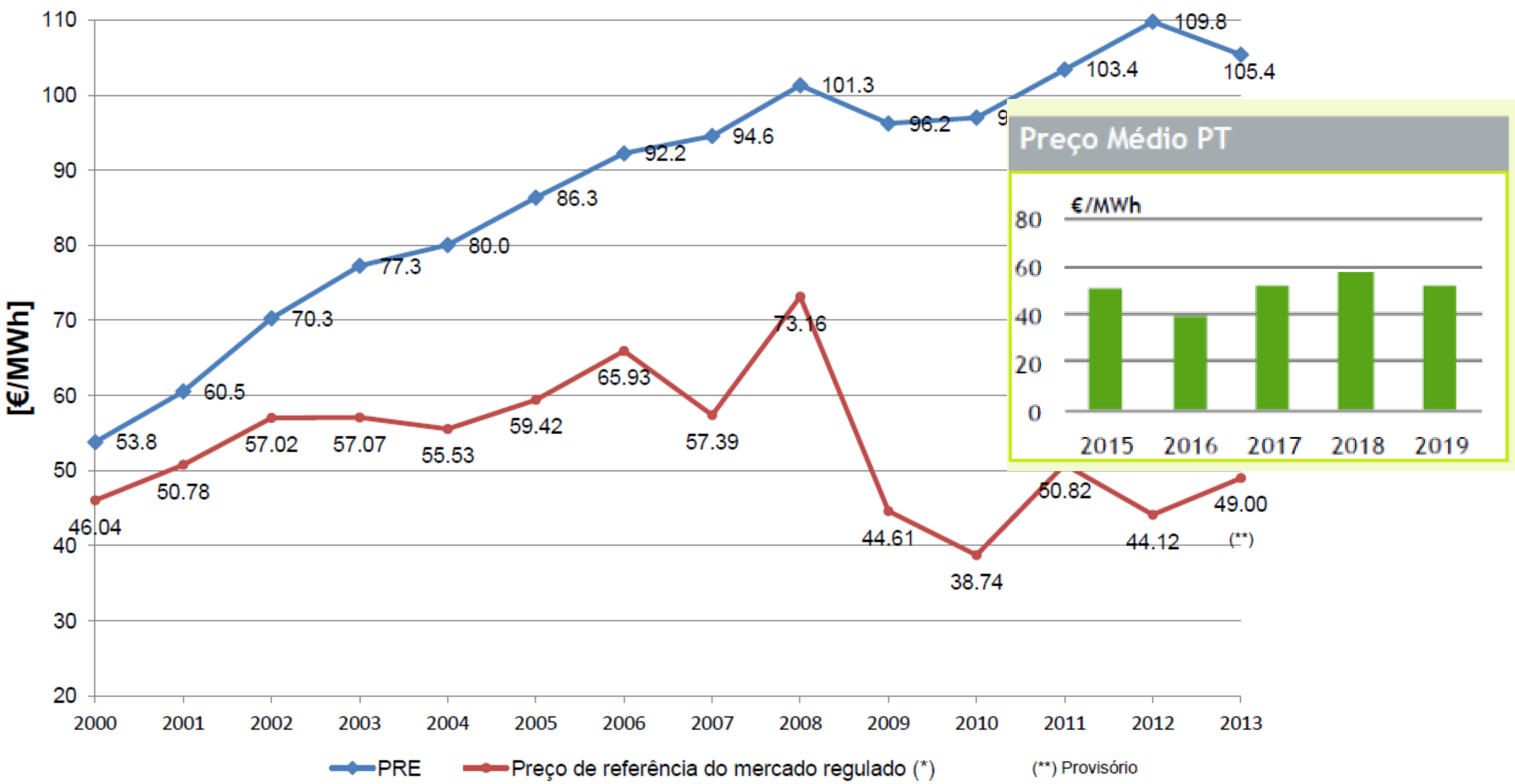
Estimated costs



RENEWABLE ENERGY PRICES AND COSTS

Average annual prices

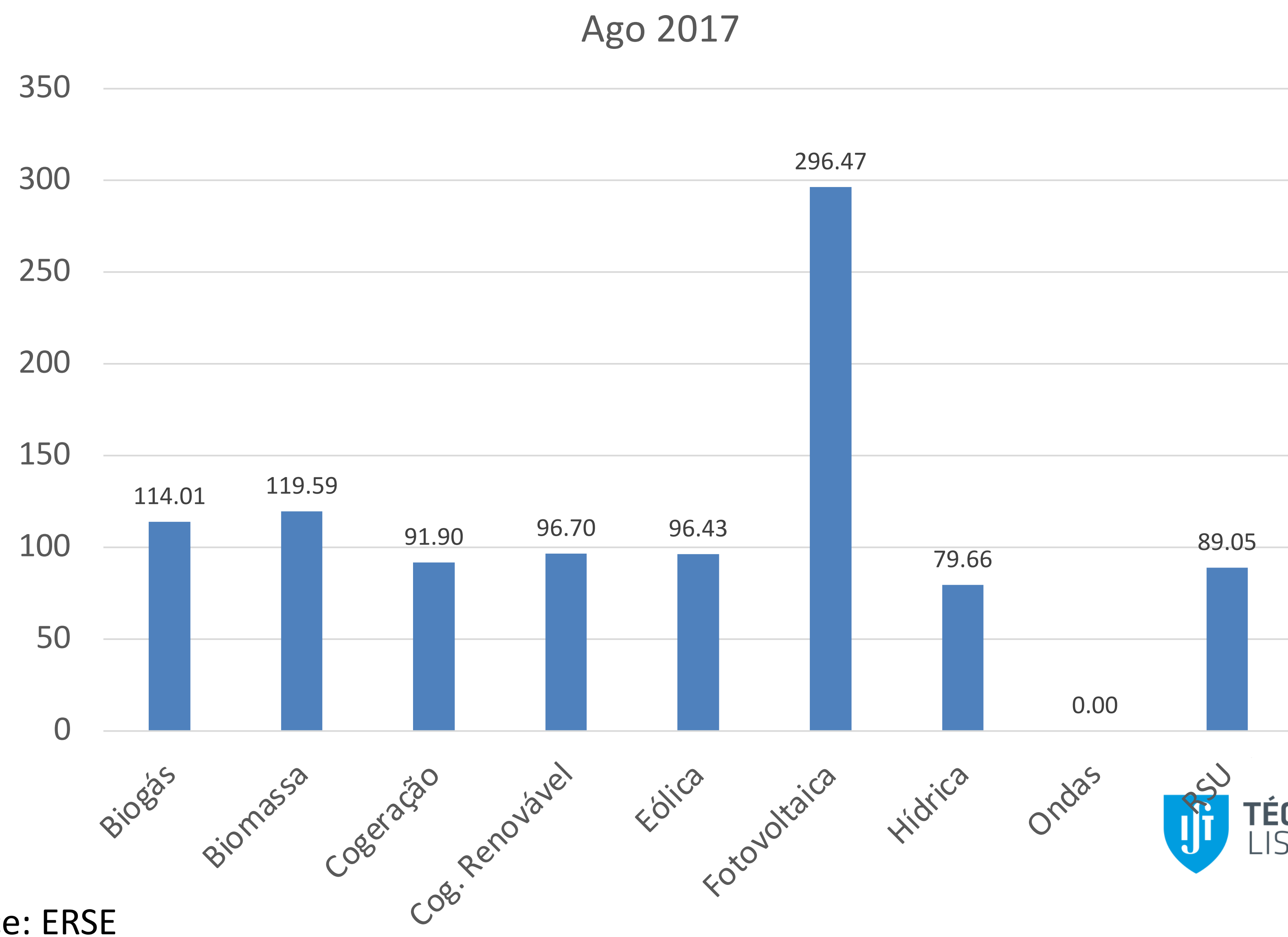
FIT (Ago2017): 104.12 €/MWh



MIBEL spot price (€/MWh)
(2017): 52.5; (2018): 57.4; (2019): 47.87

Source: ERSE

FIT per technology



Source: ERSE

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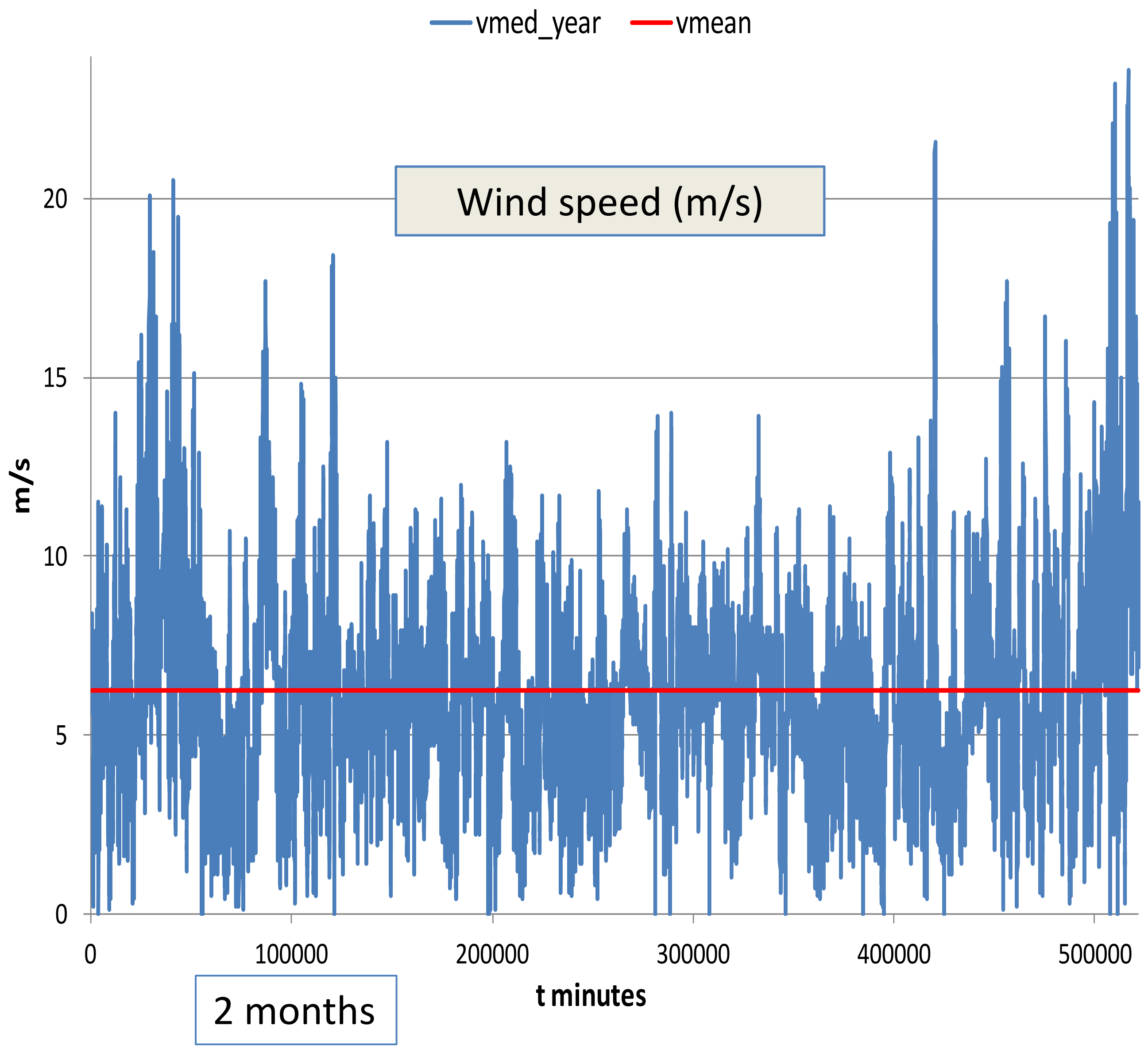
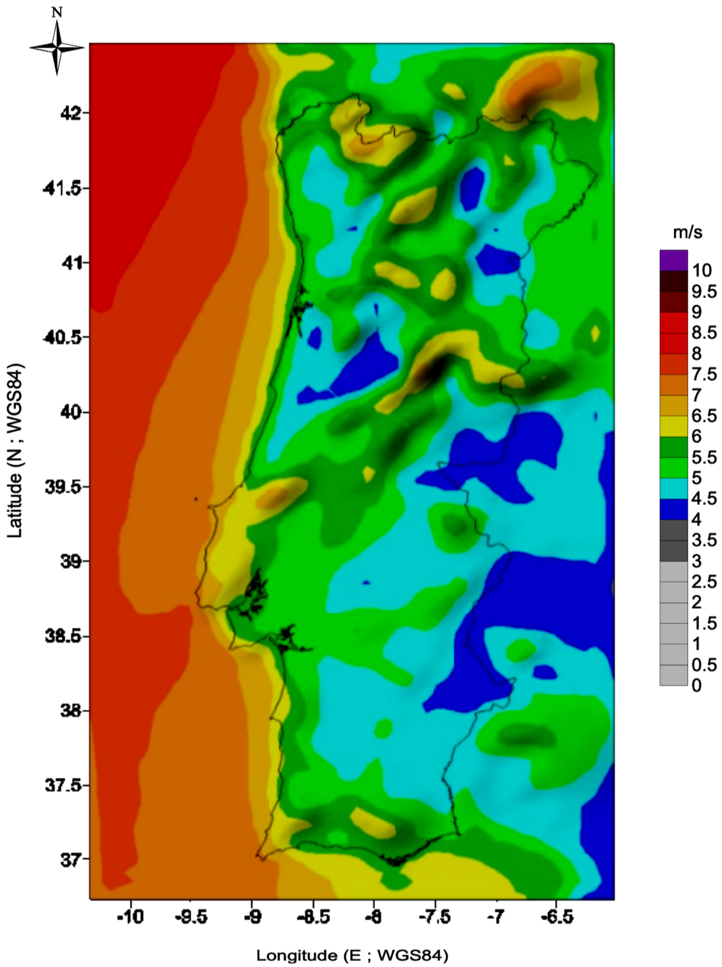
WIND CHARACTERISTICS

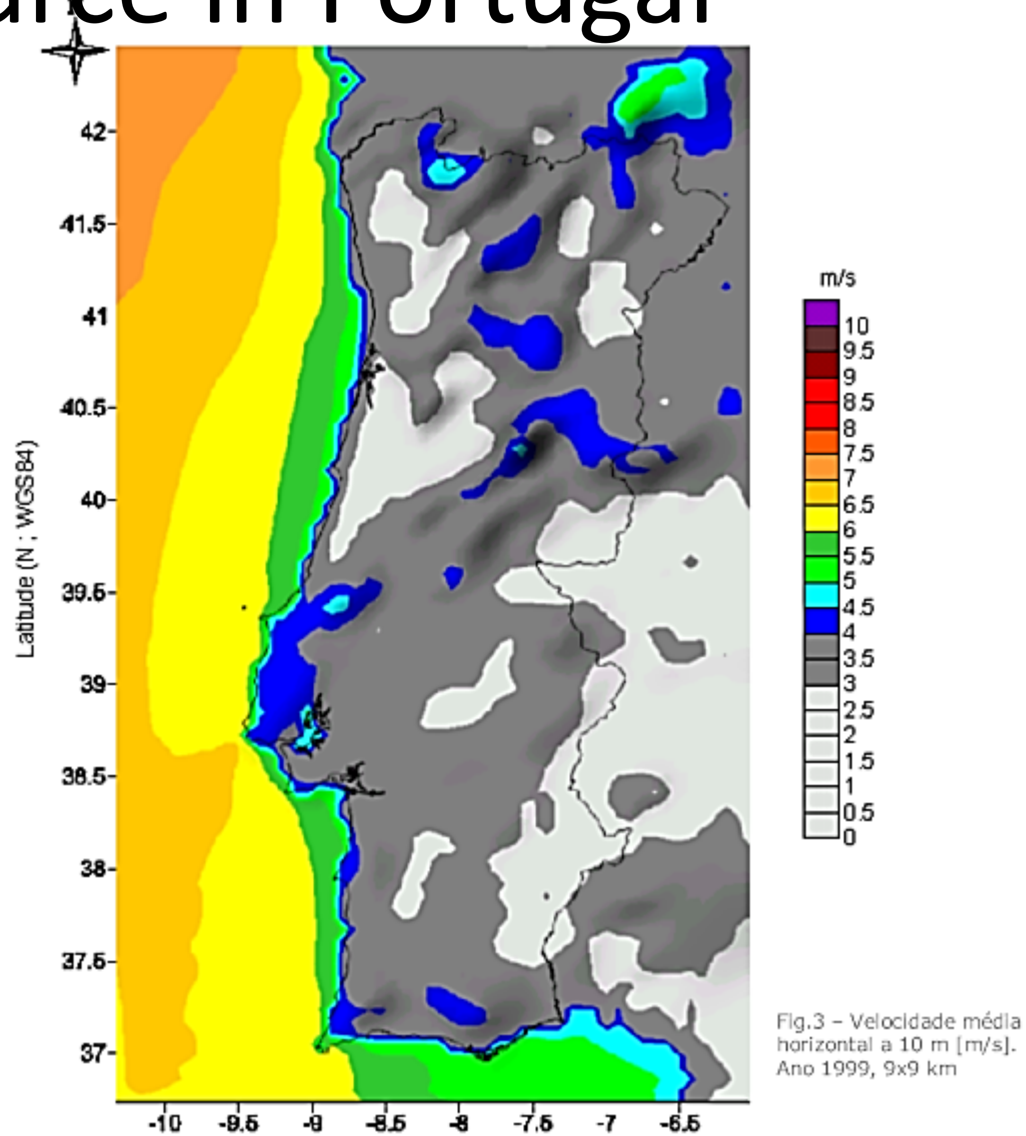
Variations in time



Wind resource in Portugal

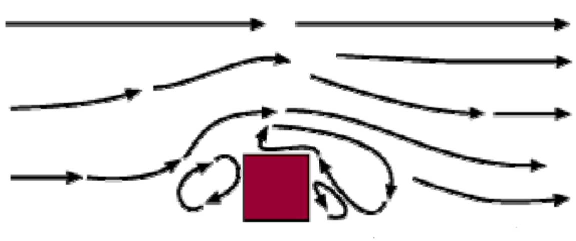


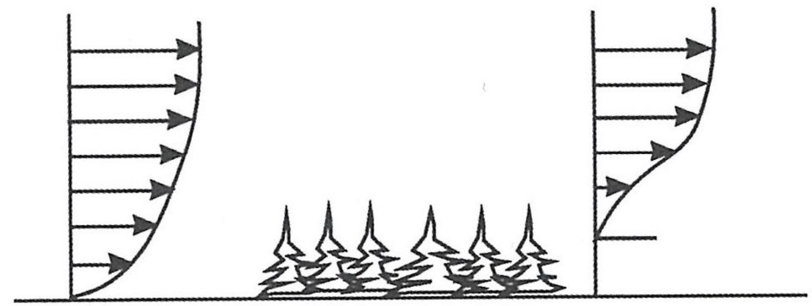
Average wind speed at 60m

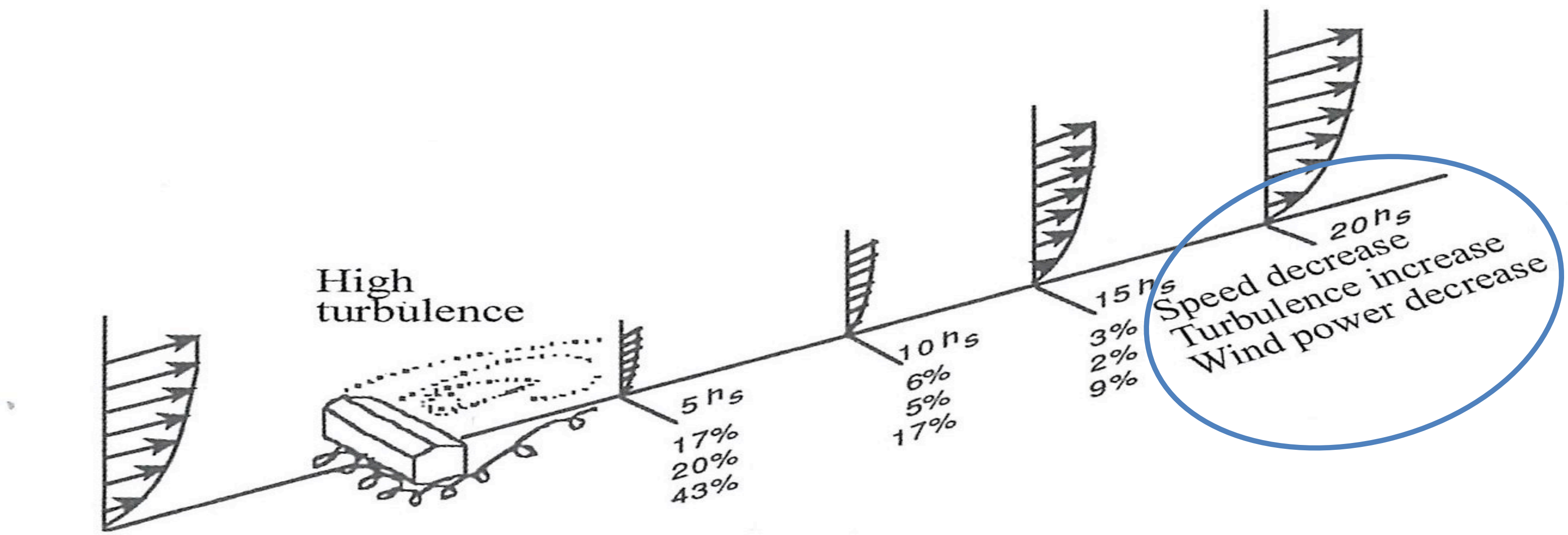


Average wind speed at 10m

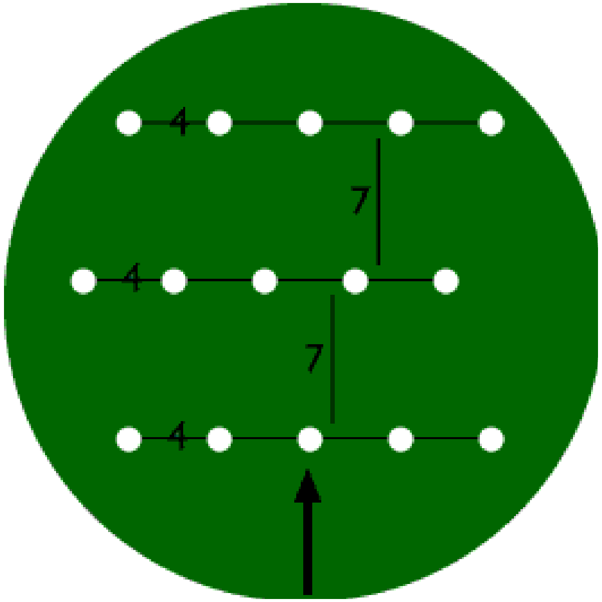
Effect of terrain





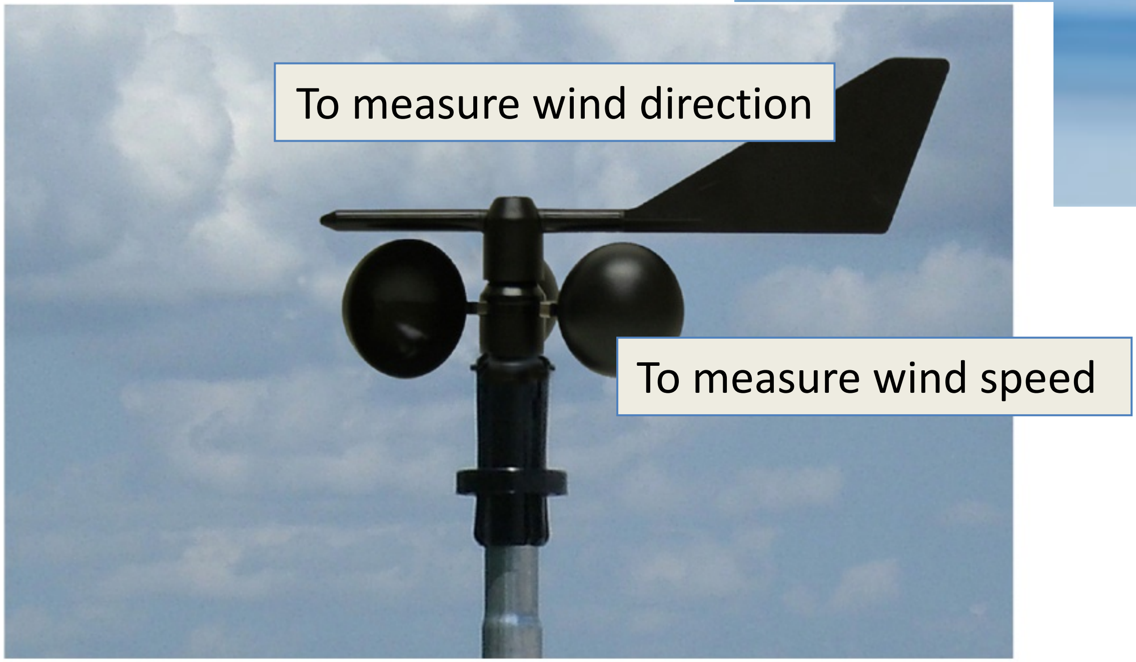


Wake effect



Recommended distances between turbines (as a function of rotor diameter) in order to minimize wake effect

Anemometers

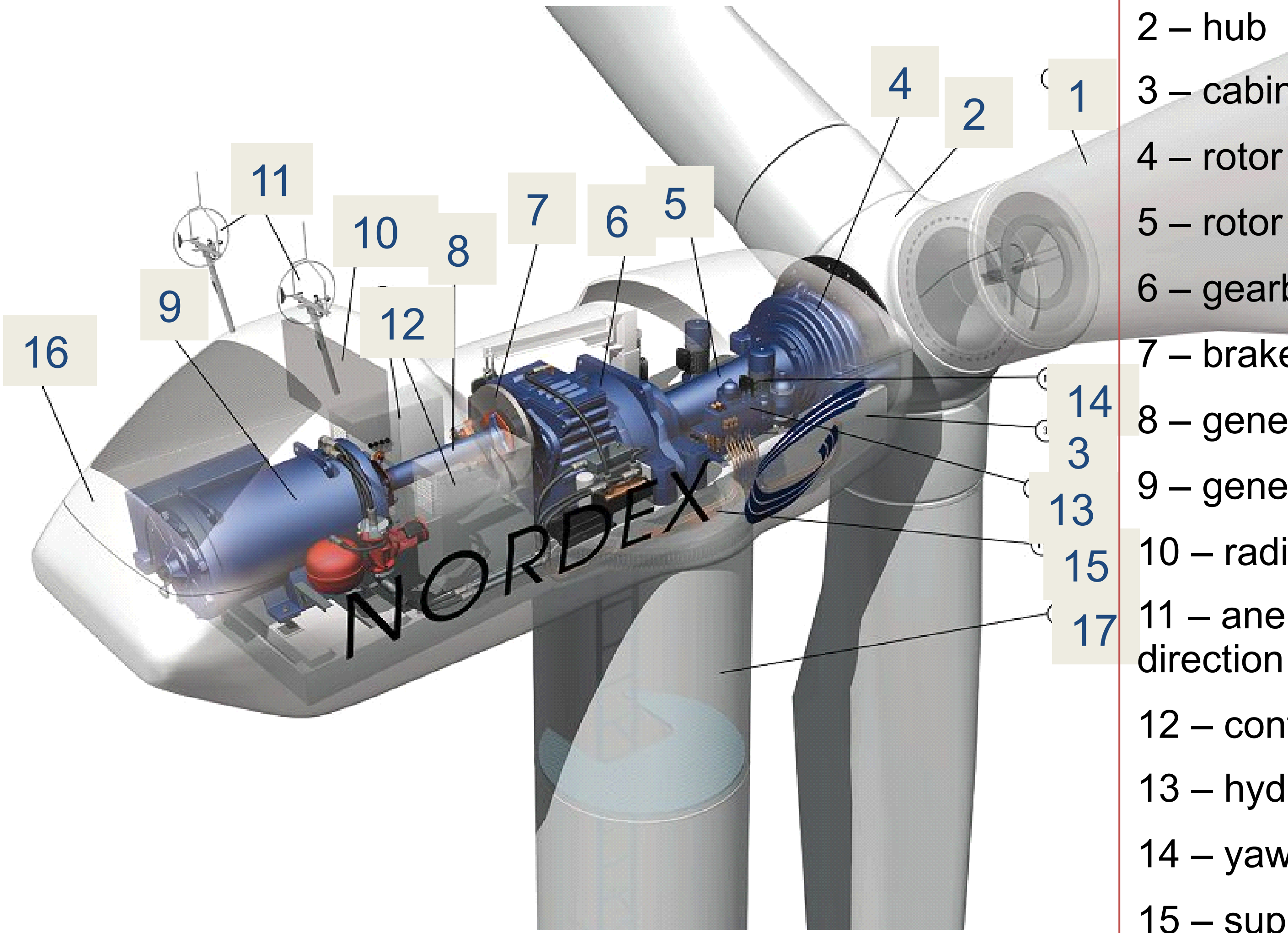


WIND GENERATOR COMPONENTS

Rotor, nacelle and tower

- Rotor
  - Upwind / Downwind
  - Solidity / Number of blades
  - Flexible blades
  - Blade material: Glass Reinforced Plastic; Carbon Fiber (expensive, best choice); Wood-Epoxy laminates
- Cabin (Nacelle)
  - Main shaft
  - Disk brakes
  - Gearbox (if it exists)
  - Generator
  - Yaw mechanism
- Tower
  - Tubular / Trusses

Components



1 – rotor blades

2 – hub

3 – cabin

4 – rotor support bearing

5 – rotor shaft

6 – gearbox

7 – brake

8 – generator shaft

9 – generator

10 – radiator

11 – anemometer and direction sensor

12 – control system

13 – hydraulic system

14 – yaw mechanism

15 – support bearing of the yaw

16 – cabin cover

17 – tower

Nacelle – 75 tons
Rotor – 40 tons
Tower – 152 tons
Total – 267 tons

Vestas [V90](#) [V903d](#)

Rotor Diameter: 90 m
Area swept: 6 362 m2
Nominal revolutions: 16.1 rpm
Operational interval: 8.6 - 18.4 rpm
Number of blades: 3
Hub height: 80 - 105 m
Cut-in wind speed: 4 m/s
Nominal wind speed (3 000 kW): 15 m/s
Cut-out wind speed: 25 m/s

WIND DATA ANALYSIS

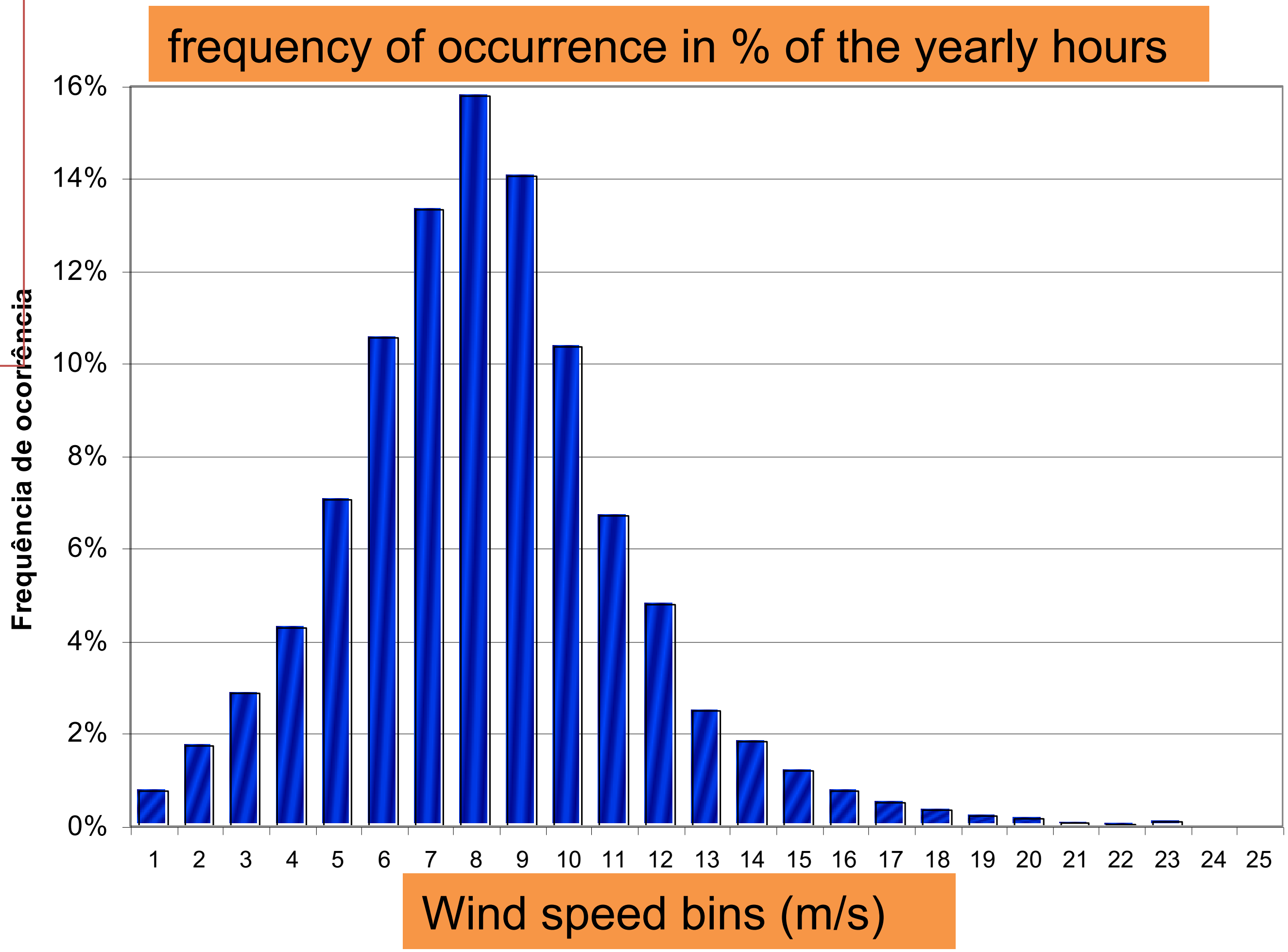
Methods

- Method of bins
  - Histogram
  - Data separated in data intervals (bins) of width 1m/s with f_j occurrences

- Statistical analysis
  - Weibull distribution
  - Rayleigh distribution

Method of bins

h	u	classe
8679	6,50	7
8680	8,38	8
8681	9,75	10
8682	9,76	10
8683	10,98	11
8684	10,64	11
8685	11,76	12
8686	13,72	14
8687	15,42	15
8688	16,94	17



Weibull pdf

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{u}{c}\right)^{k}\right)$$

pdf: probability density function

Probability of the wind speed to be equal to a particular value u

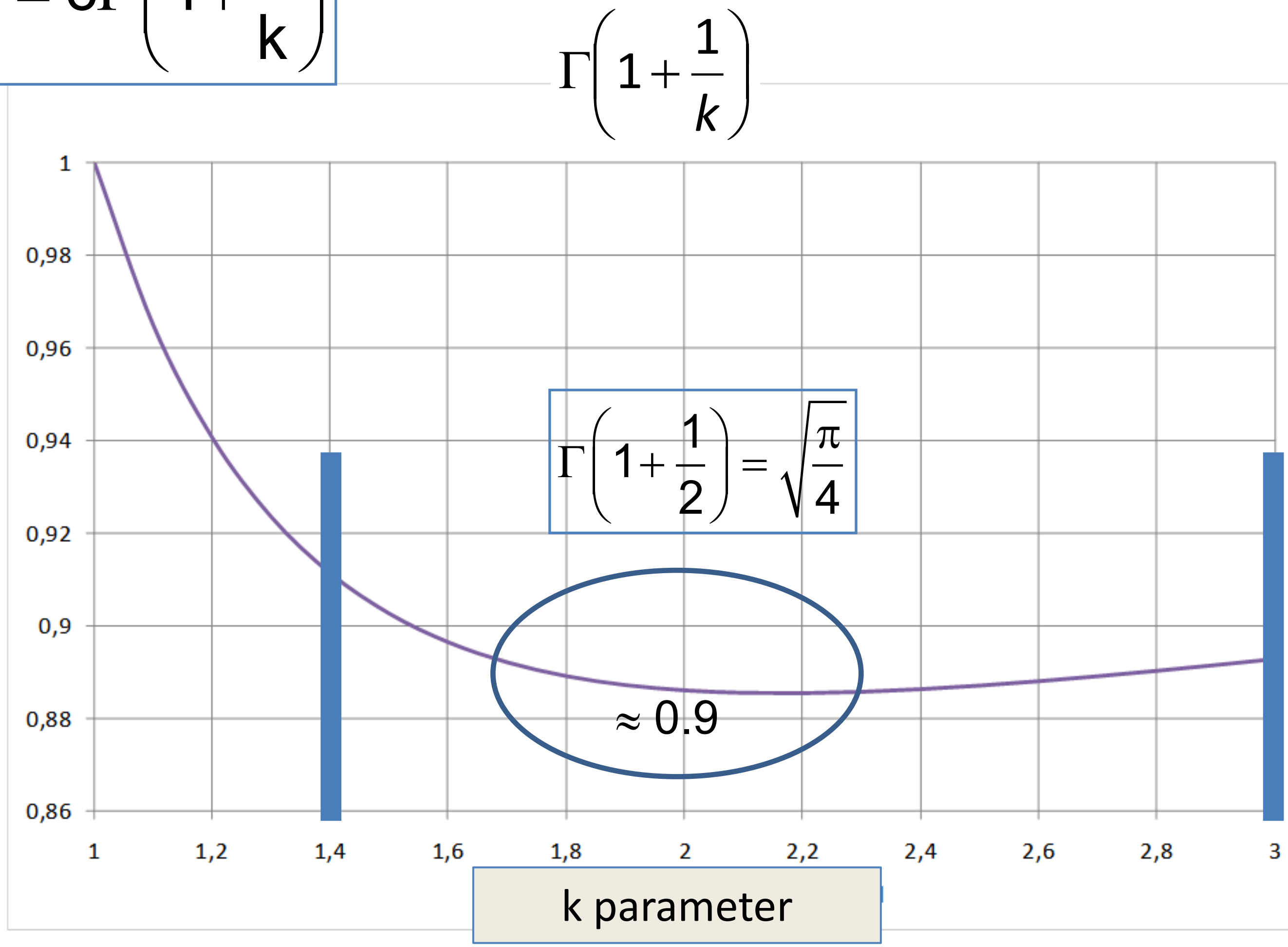
k > 0 is the shape parameter
c > 0 is the scale parameter (m/s)

$$u_{ma} = \int_0^{\infty} u\, f(u)\, du \quad \Rightarrow \quad u_{ma} = \sum_{\bar{u}=0}^{\bar{u}_{max}} u\, f(u)$$

Annual mean wind speed

Gamma function

$$u_{ma} = c\Gamma\left(1+\frac{1}{k}\right)$$



Weibull cdf

$$F(u) = 1 - \int_{-\infty}^{u} f(u)\,du = 1 - \int_{0}^{u} f(u)\,du$$

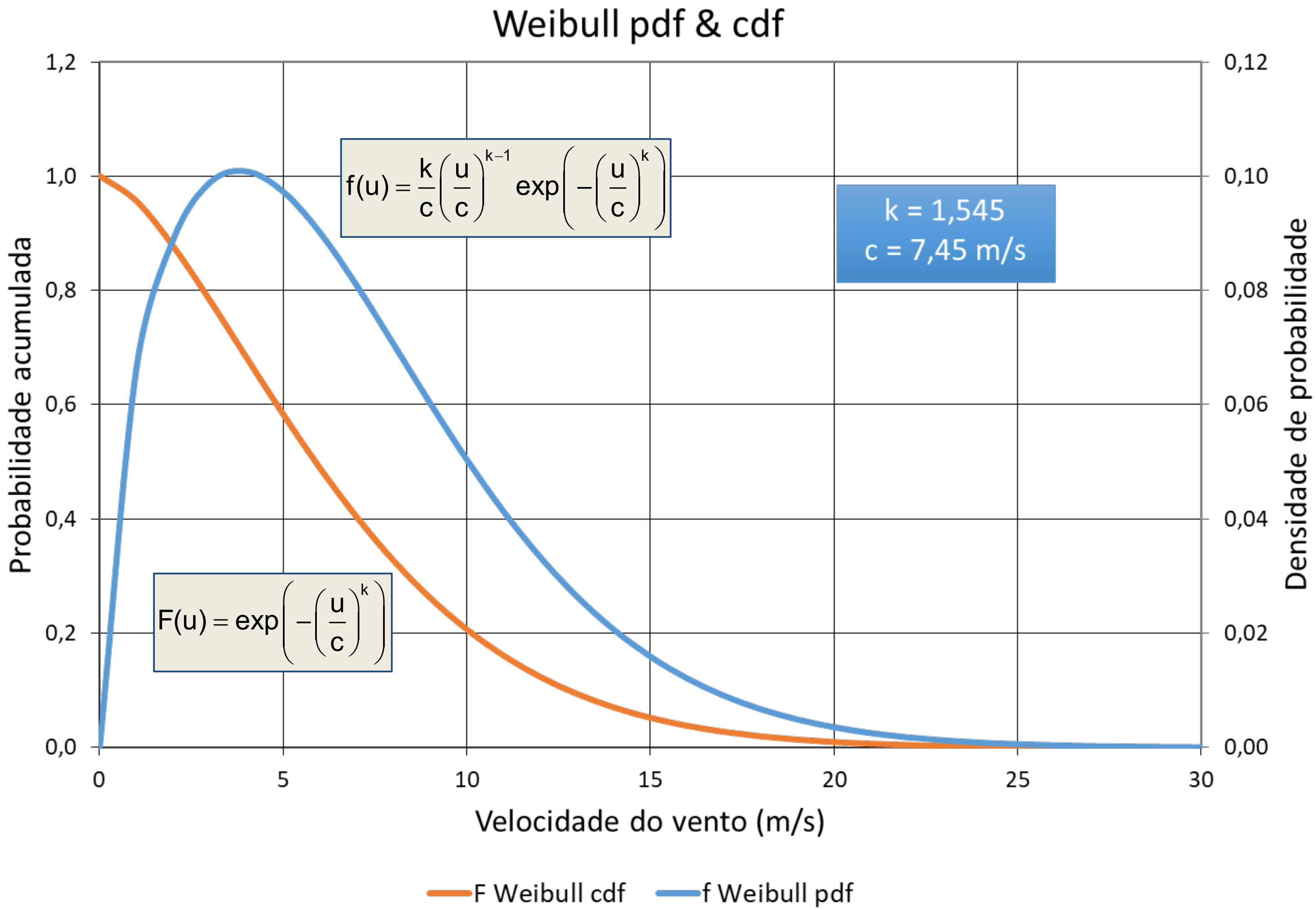
Probability of the wind speed to exceed a particular value

$$f(u) = -\frac{dF(u)}{du}$$

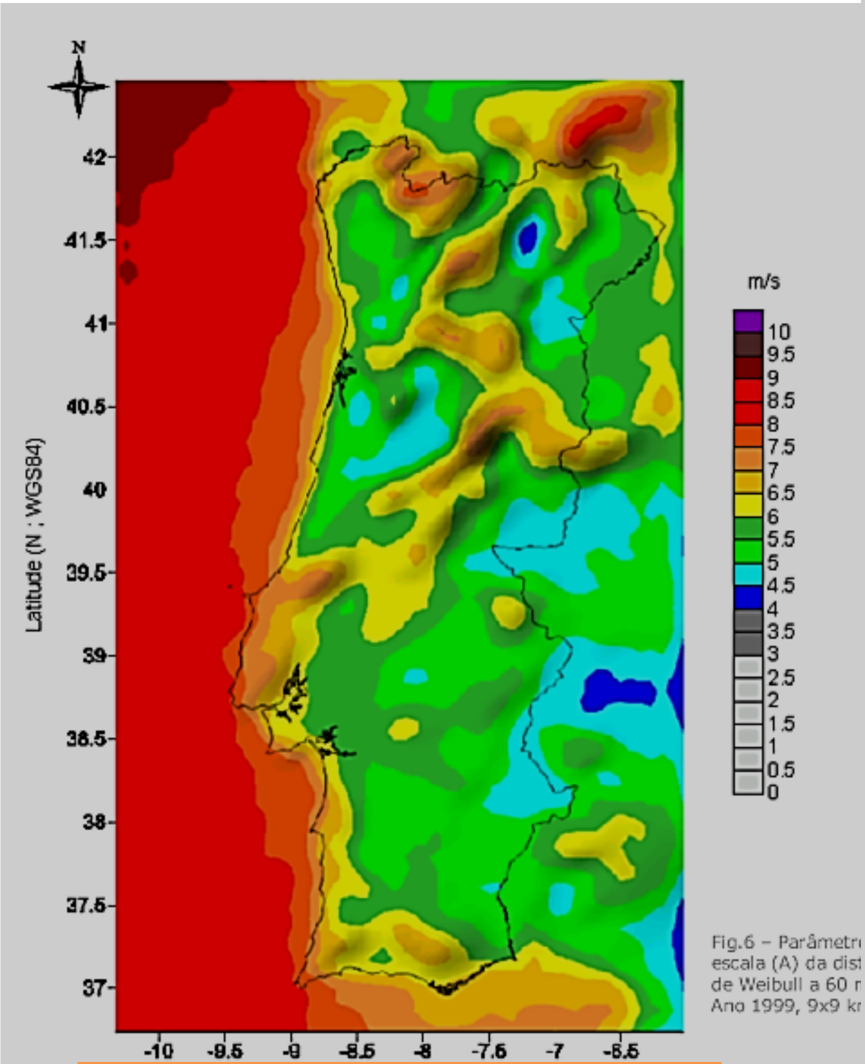
cdf: cumulative distribution function

$$F(u) = \exp\left(-\left(\frac{u}{c}\right)^{k}\right)$$

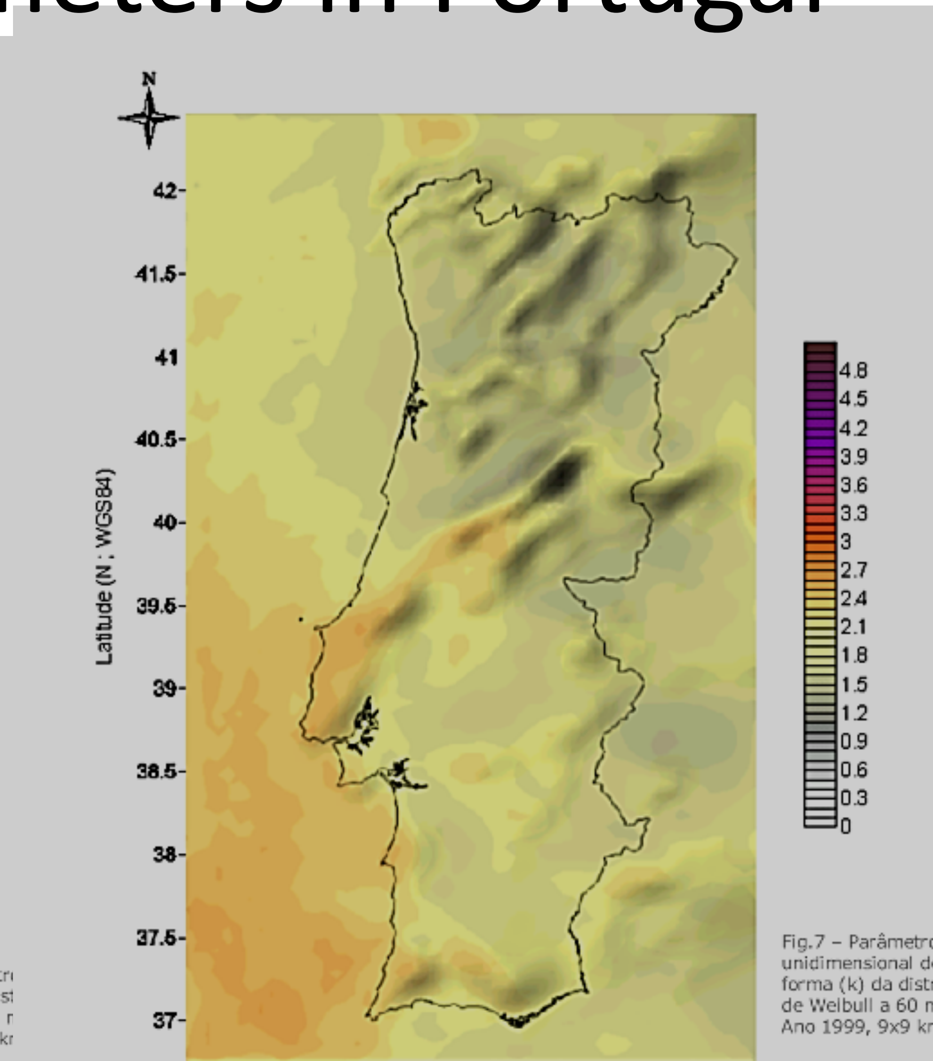
Weibull pdf & cdf



Weibull parameters in Portugal



c parameter (60 m height)

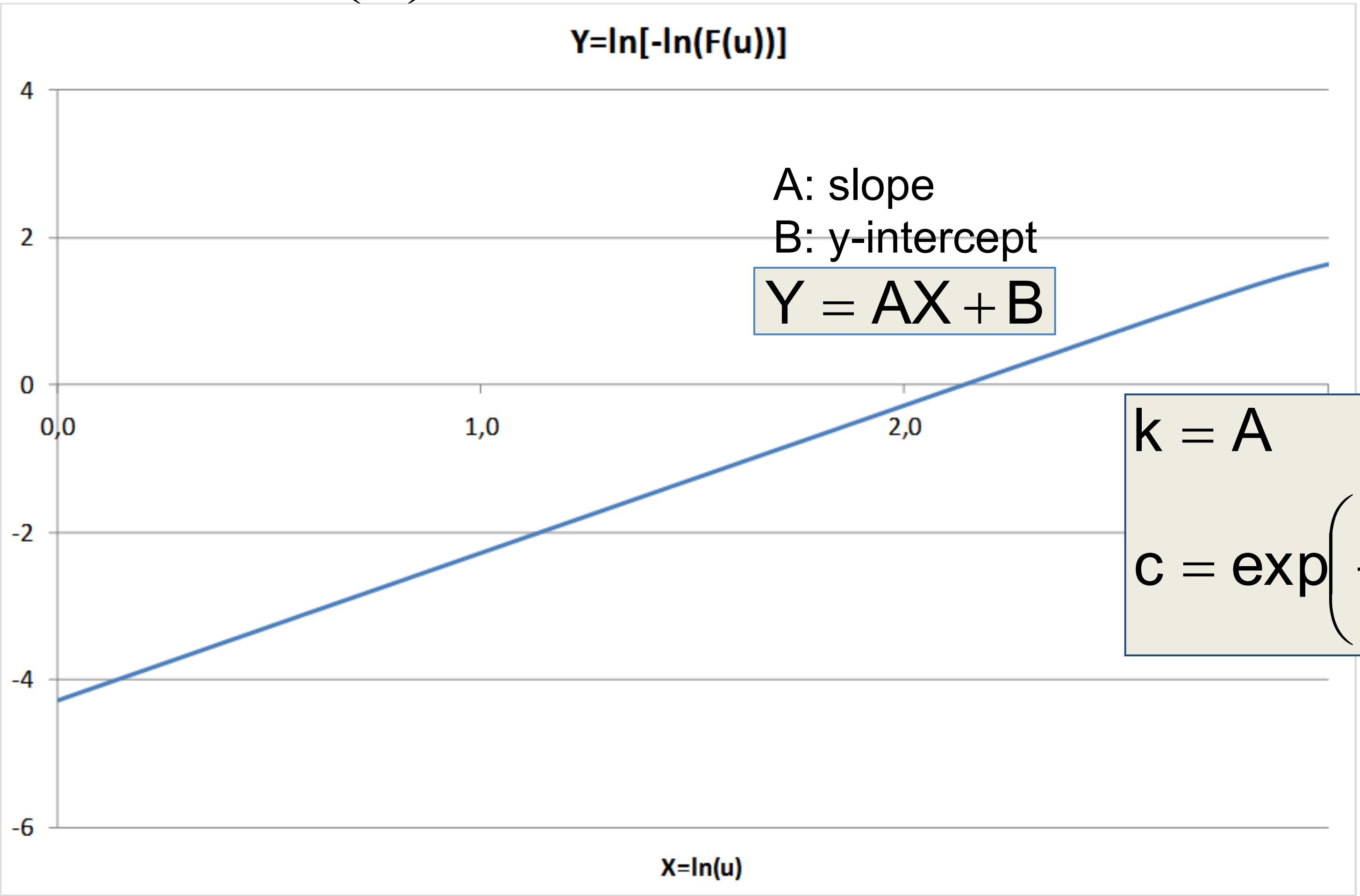


k parameter (60 m height)

$$F(u) = \exp\left(-\left(\frac{u}{c}\right)^k\right)$$

Weibull parameters estimation

$$\ln[F(u)] = -\left(\frac{u}{c}\right)^k \rightarrow \ln\left[-\ln(F(u))\right] = k\ln(u) - k\ln(c)$$



A: slope
B: y-intercept

$$Y = AX + B$$

$$k = A$$

$$c = \exp\left(-\frac{B}{A}\right)$$

Weibull parameters estimation
Least Squares Method

- Given data: known experimental histogram
- Modern solution
- **Excel solver**
  - Objective: compute the best fit k and c, by minimizing the mean square error
  - Guess initial values
  - Change k and c, in order to minimize the quadratic error

Weibull parameters estimation
Least Squares Method

Initial values

	f(u)_Experim.	f(u)_LS	E_QUAD
1	0,028	0,090	0,00396
2	0,053	0,082	0,00084
3	0,074	0,074	0,00000
4	0,089	0,067	0,00050
5	0,099	0,061	0,00143
6	0,101	0,055	0,00216
7	0,099	0,050	0,00240
8	0,091	0,045	0,00216

WEIBULL_LS	
k	c
1,00	10,00
Av_E_QUAD	0,01798

Final values

	f(u)_Experim.	f(u)_LS	E_QUAD
1	0,028	0,028	0,00000
2	0,053	0,053	0,00000
3	0,074	0,074	0,00000
4	0,089	0,089	0,00000
5	0,099	0,099	0,00000
6	0,101	0,101	0,00000
7	0,099	0,099	0,00000
8	0,091	0,091	0,00000

WEIBULL_LS	
k	c
2,00	8,46
Av_E_QUAD	0,00000

Rayleigh distribution

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{\bar{u}}{c}\right)^{k}\right)$$

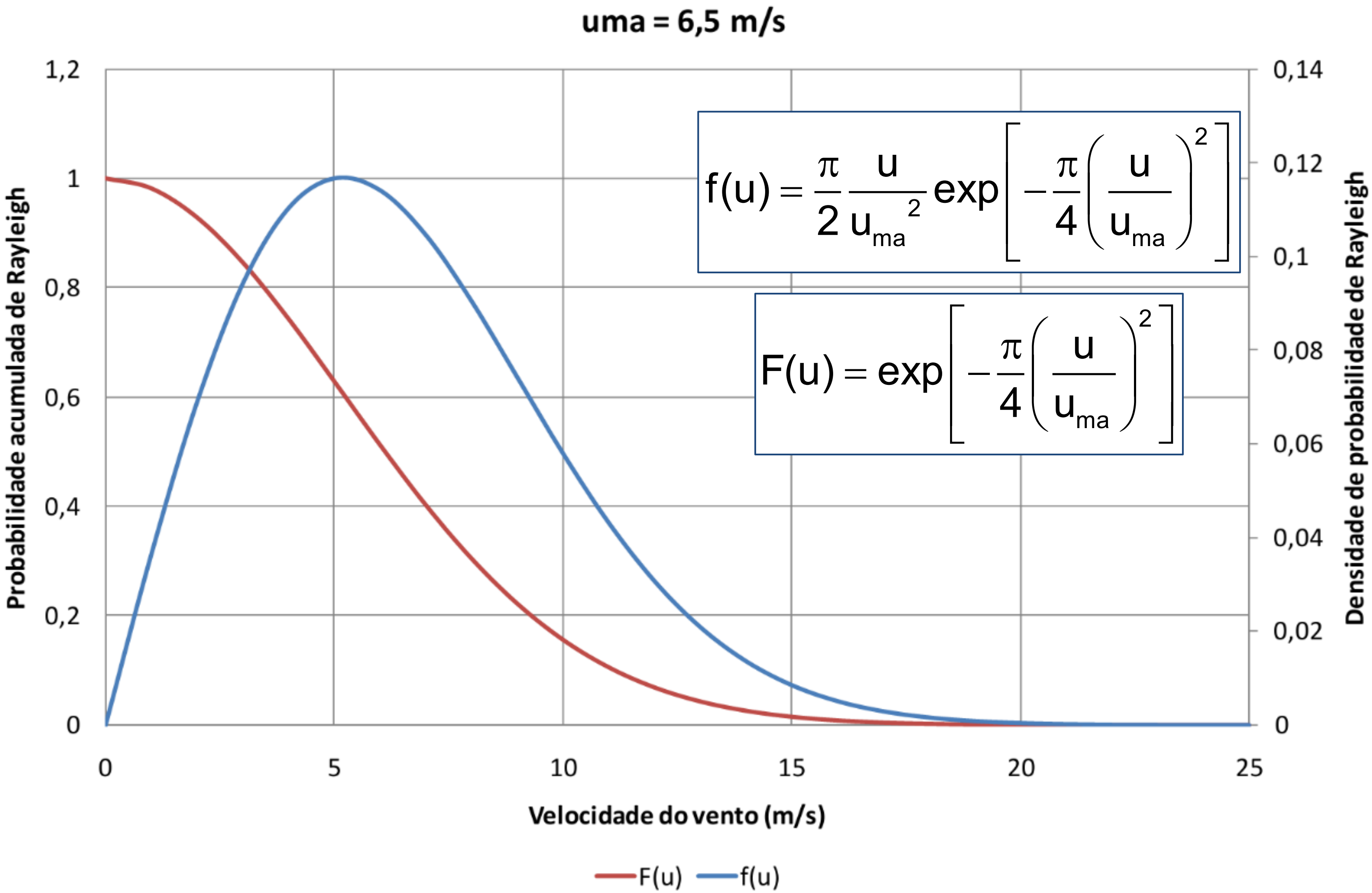
Weibull with k=2

$$c = \frac{u_{ma}}{\Gamma\left(1+\frac{1}{2}\right)} = \frac{2}{\sqrt{\pi}} u_{ma}$$

$$f(u) = \left(\frac{\sqrt{\pi}}{u_{ma}}\right)\left(\frac{u\sqrt{\pi}}{2u_{ma}}\right) \exp\left\{-\left[\left(\frac{u\sqrt{\pi}}{2u_{ma}}\right)^{2}\right]\right\}$$

$$f(u) = \frac{\pi}{2}\frac{u}{u_{ma}{}^{2}} \exp\left[-\frac{\pi}{4}\left(\frac{u}{u_{ma}}\right)^{2}\right]$$

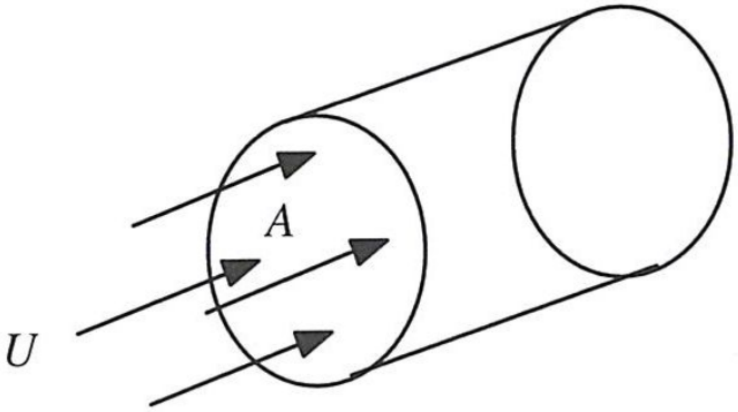
Rayleigh pdf & cdf



POWER IN THE WIND

Available power in the wind

$$E_{cin} = \frac{1}{2} m u^2 = \frac{1}{2} (\rho A x) u^2$$



m: mass of the volume of air (kg)
u: constant speed of air (m/s)
ρ: air density (1,23 kg/m³, θ=15ºC)
A: area of the disk of air (m²)
x: thickness of the volume of air (m)

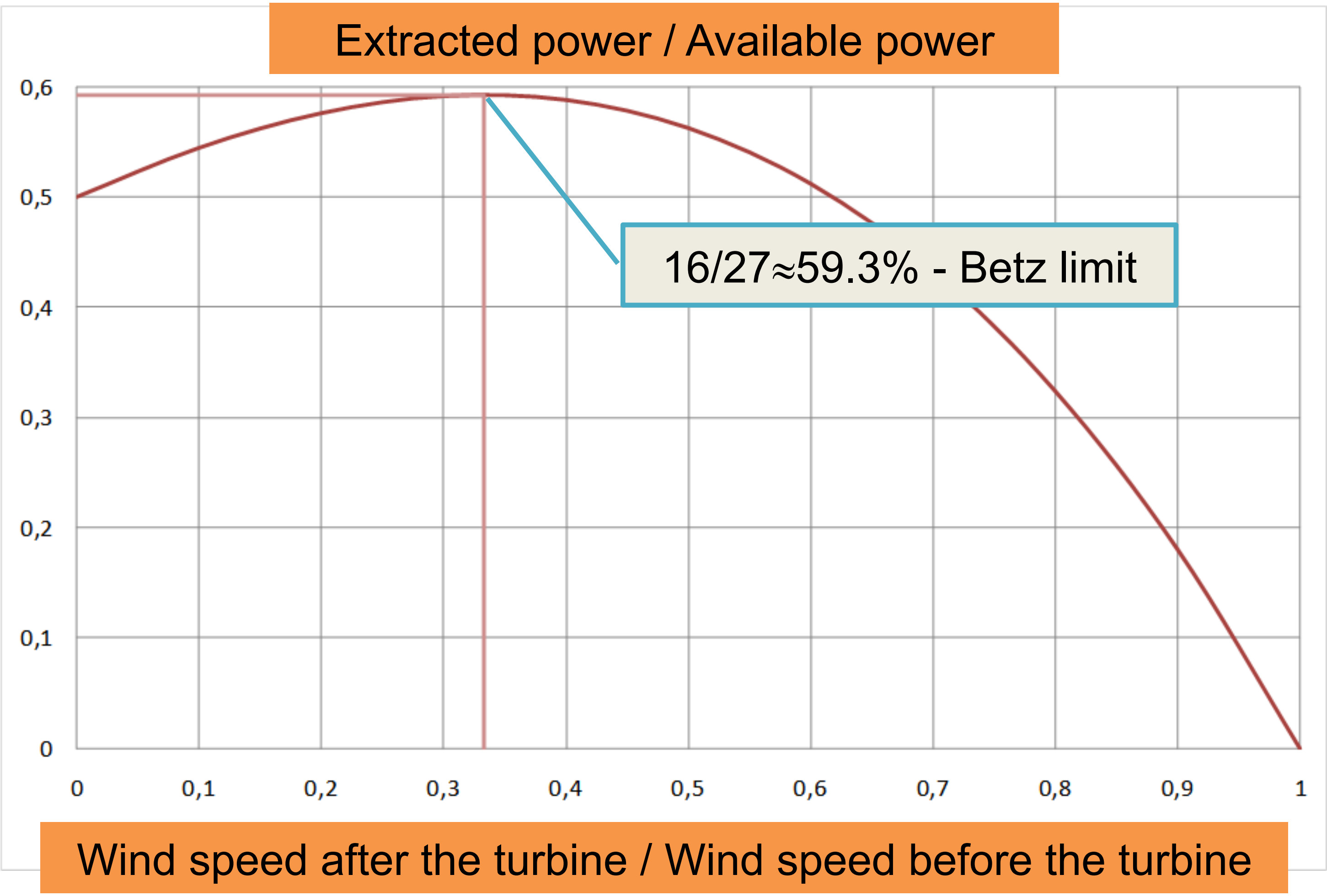
Available power in the wind

$$P_{avail} = \frac{dE_{kin}}{dt} = \frac{1}{2}\left(\rho A \frac{dx}{dt}\right) u^2$$

$$P_{avail} = \frac{1}{2} \rho A u^3$$

$$\frac{P_r}{P_{disp}} = \frac{1}{2}\left(1+\frac{u_2}{u_1}\right)\left[1-\left(\frac{u_2}{u_1}\right)^2\right]$$

Betz law



Currently about 45% of the available wind energy is captured by modern turbines

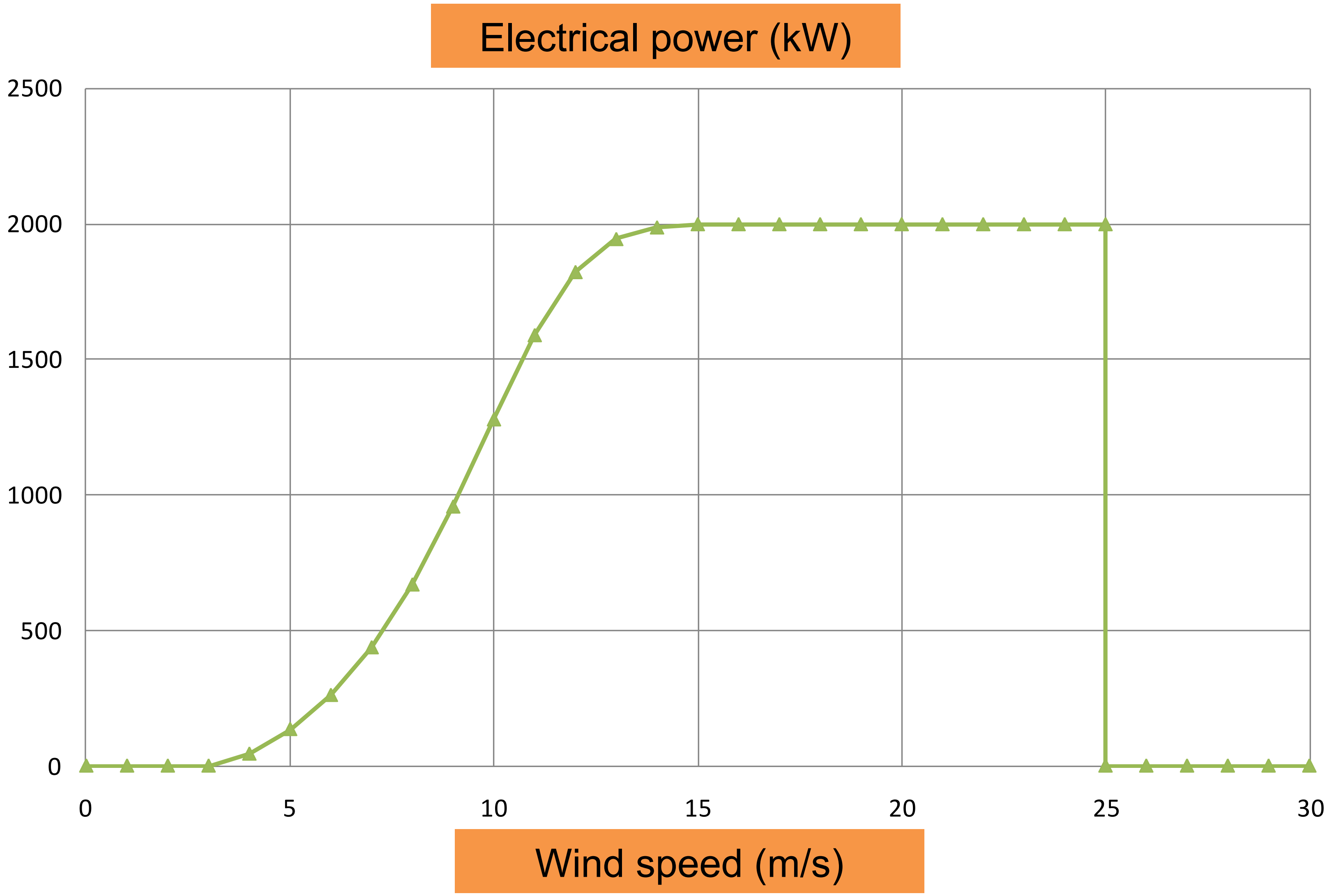
Prandtl law

$$\frac{u(z_1)}{u(z_2)} = \frac{\ln\left(z_1/z_0\right)}{\ln\left(z_2/z_0\right)}$$

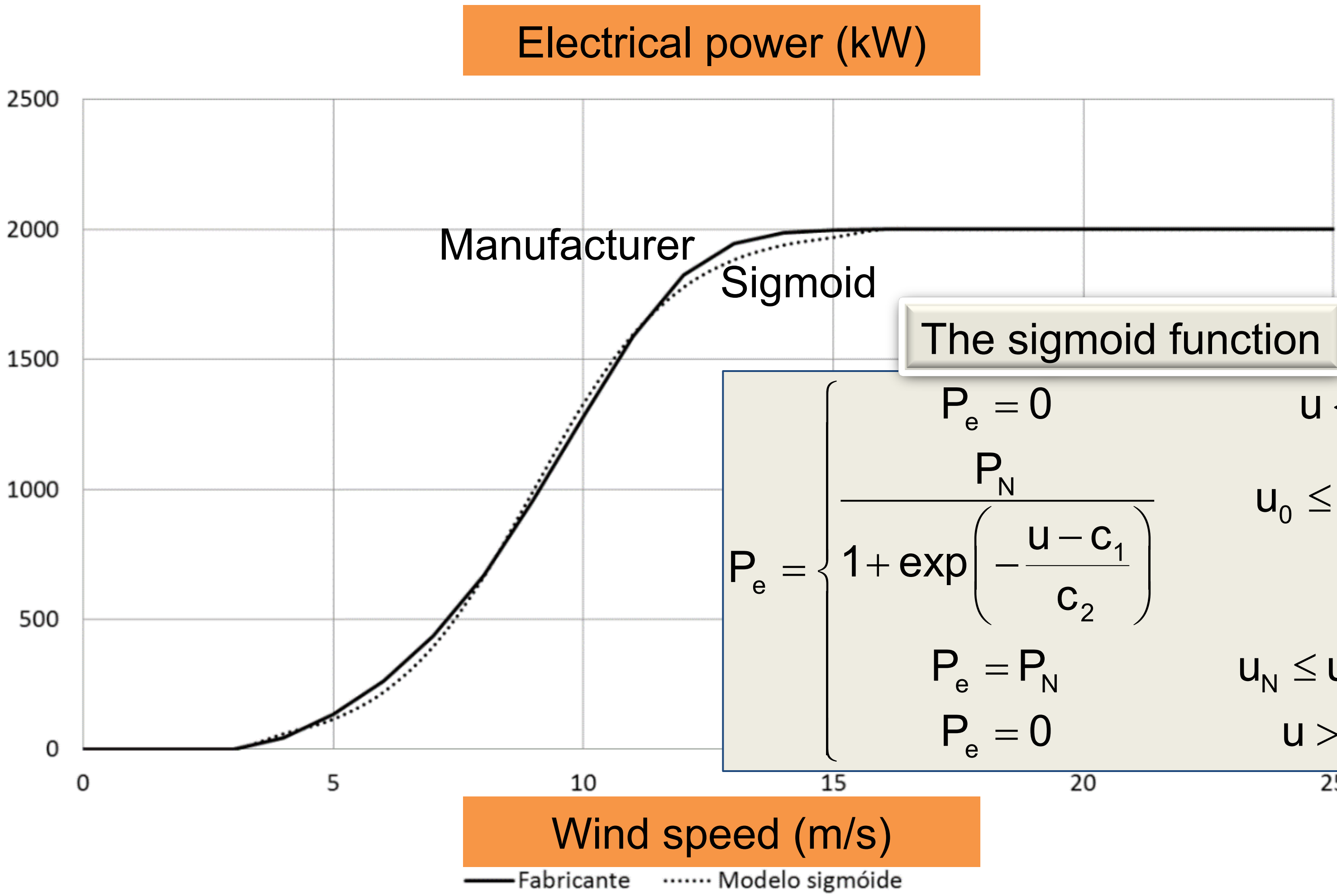
Roughness Class RC	Roughness Length, Z0 (m)	Energy Index (%)	Local Terrain Type, Landscape, Topography, Vegetation
0	0.0002	100	Water surface.
0.5	0.0024	73	Completely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills.
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1250 meters.
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters.
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 meters tall sheltering hedgerows within a distance of about 250 meters
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	18	Larger cities with tall buildings.
4	1.6	13	Very large cities with tall buildings and sky scrapers.

POWER CURVE

Power curve


Electrical power (kW)
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Wind speed (m/s)

Analytical representation

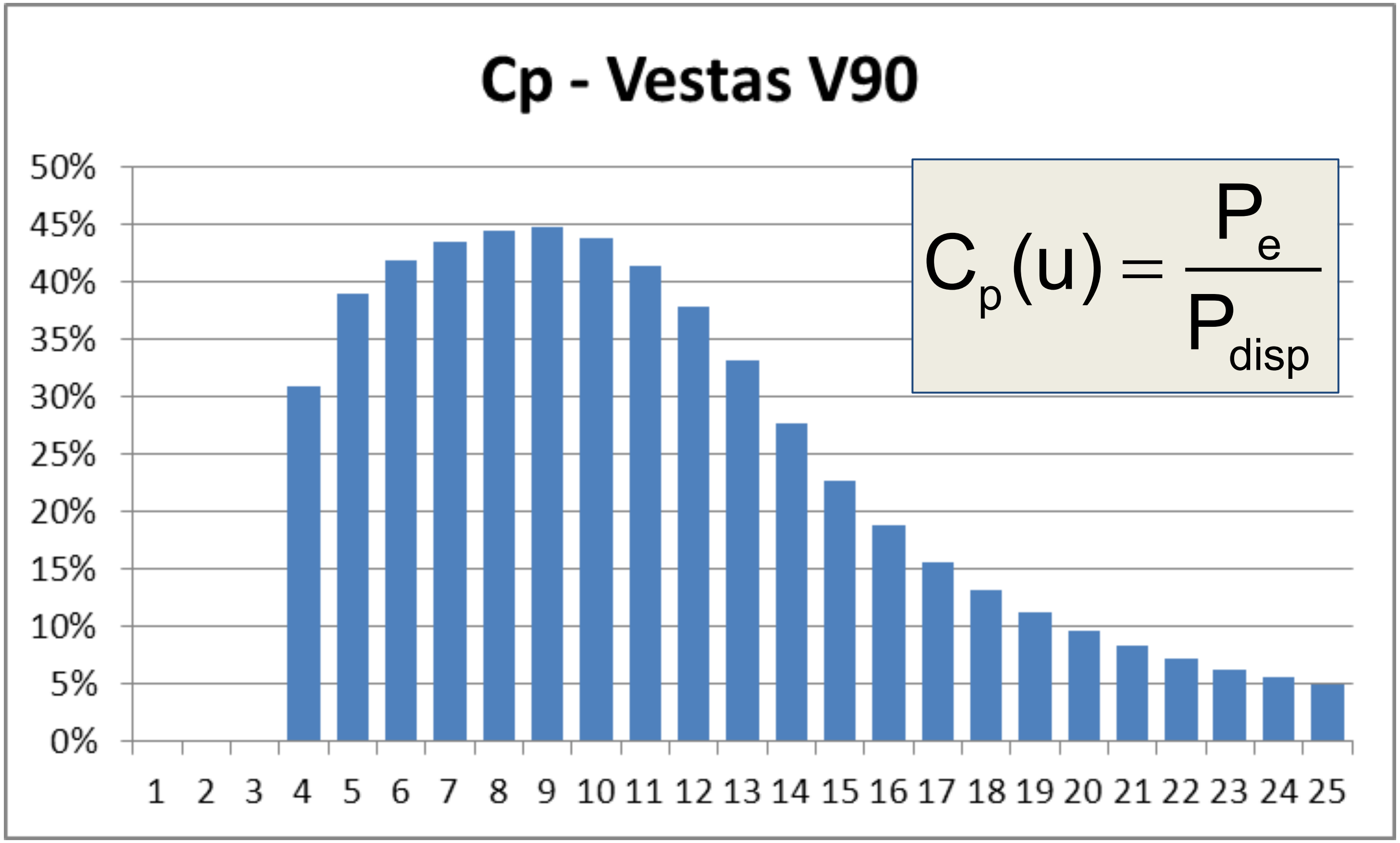


The sigmoid function

$$P_e = \begin{cases} P_e = 0 & u < u_0 \\ \dfrac{P_N}{1 + \exp\left(-\dfrac{u - c_1}{c_2}\right)} & u_0 \le u < u_N \\ P_e = P_N & u_N \le u \le u_{max} \\ P_e = 0 & u > u_{max} \end{cases}$$

Power coefficient – C_P

AKA Coefficient of performance



$$C_p(u) = \frac{P_e}{P_{disp}}$$

ENERGY PRODUCTION ESTIMATES

Methods depend on available data

Data: analytical expressions for pdf and pc

Pmed (average power)

$$E_a = 8760 \int_{u_0}^{u_{max}} f(u) P_e(u) d\bar{u}$$

f(u) – pdf
Pe(u) – power curve (pc)

Data: discrete histogram and pc

$$E_a = \sum_{u_0}^{u_{max}} f_r(u) P_e(u)$$

fr – frequency of occurrence in hours/year; fr(u)=8760f(u)

$$E_a = 8760 \sum_{i=u_1}^{u_{max}} \left[\left(F(i-1) - F(i) \right) \frac{P_e(i) + P_e(i-1)}{2} \right]$$

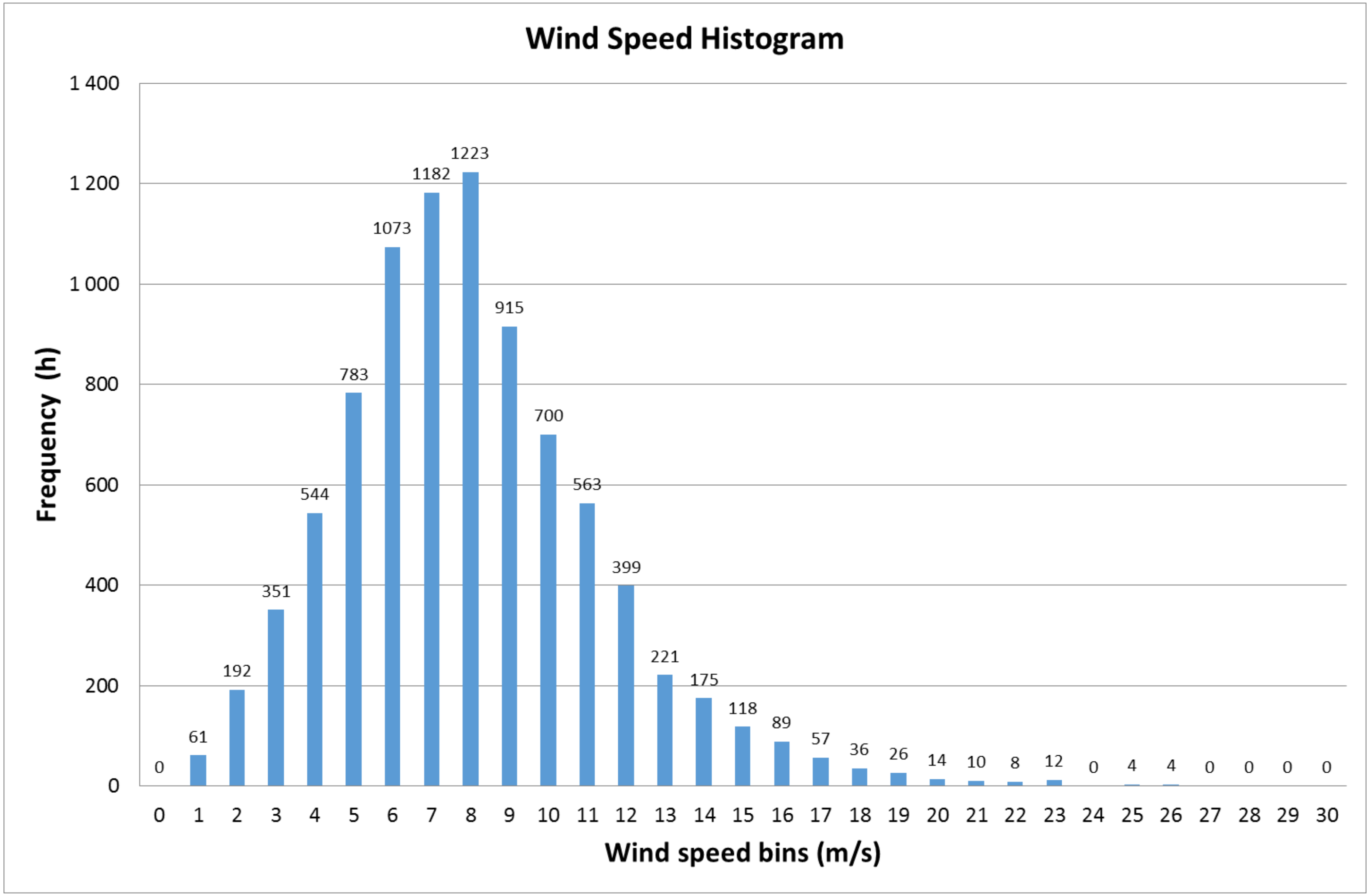
F(u) – cdf

Data: pdf analytical expression and pc discrete values

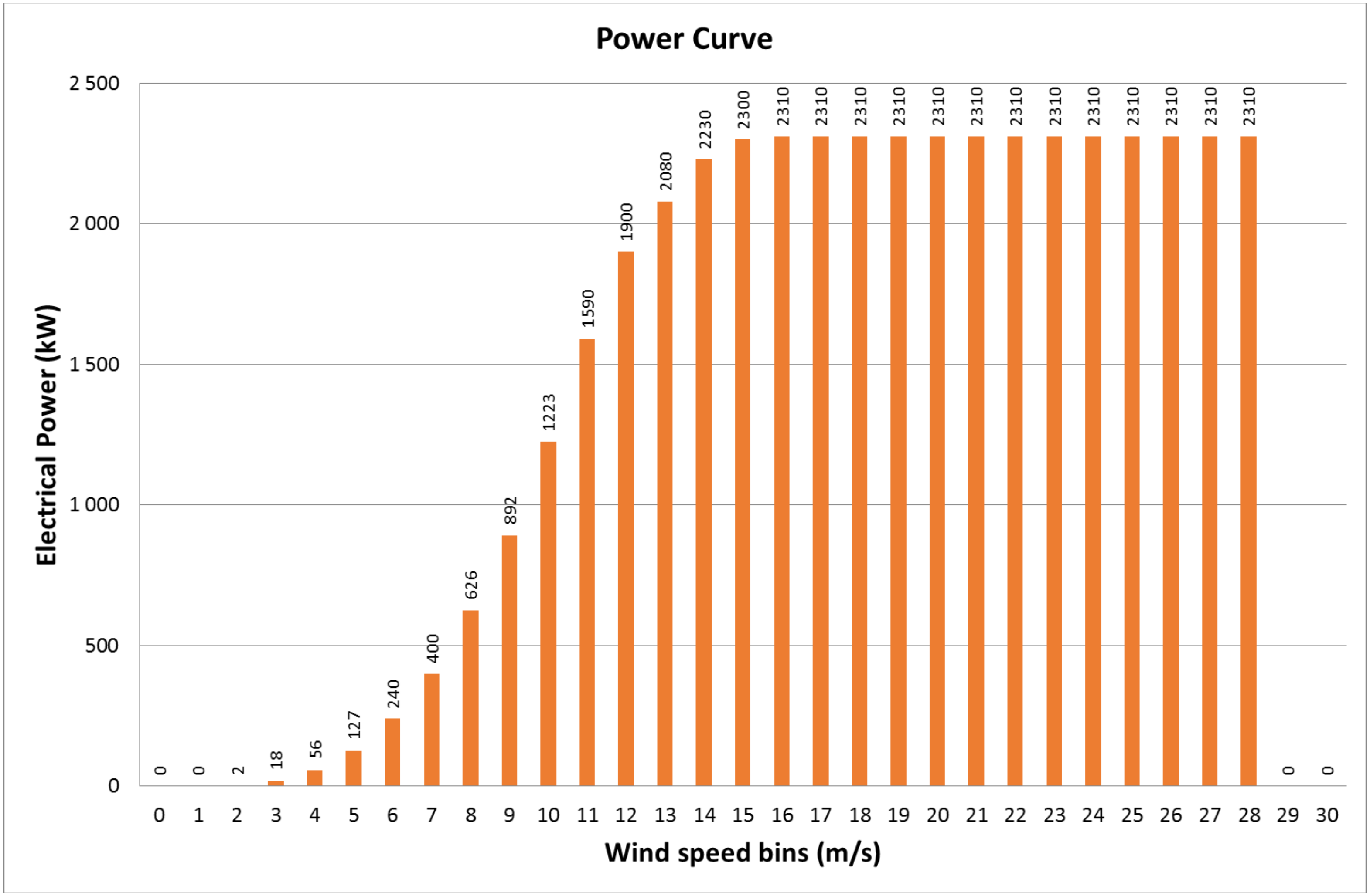
Input data

Rated power	2310kW
Rotor diameter	71m
Hub height	80m
Roughness	0.0300m
Measuring height	20m

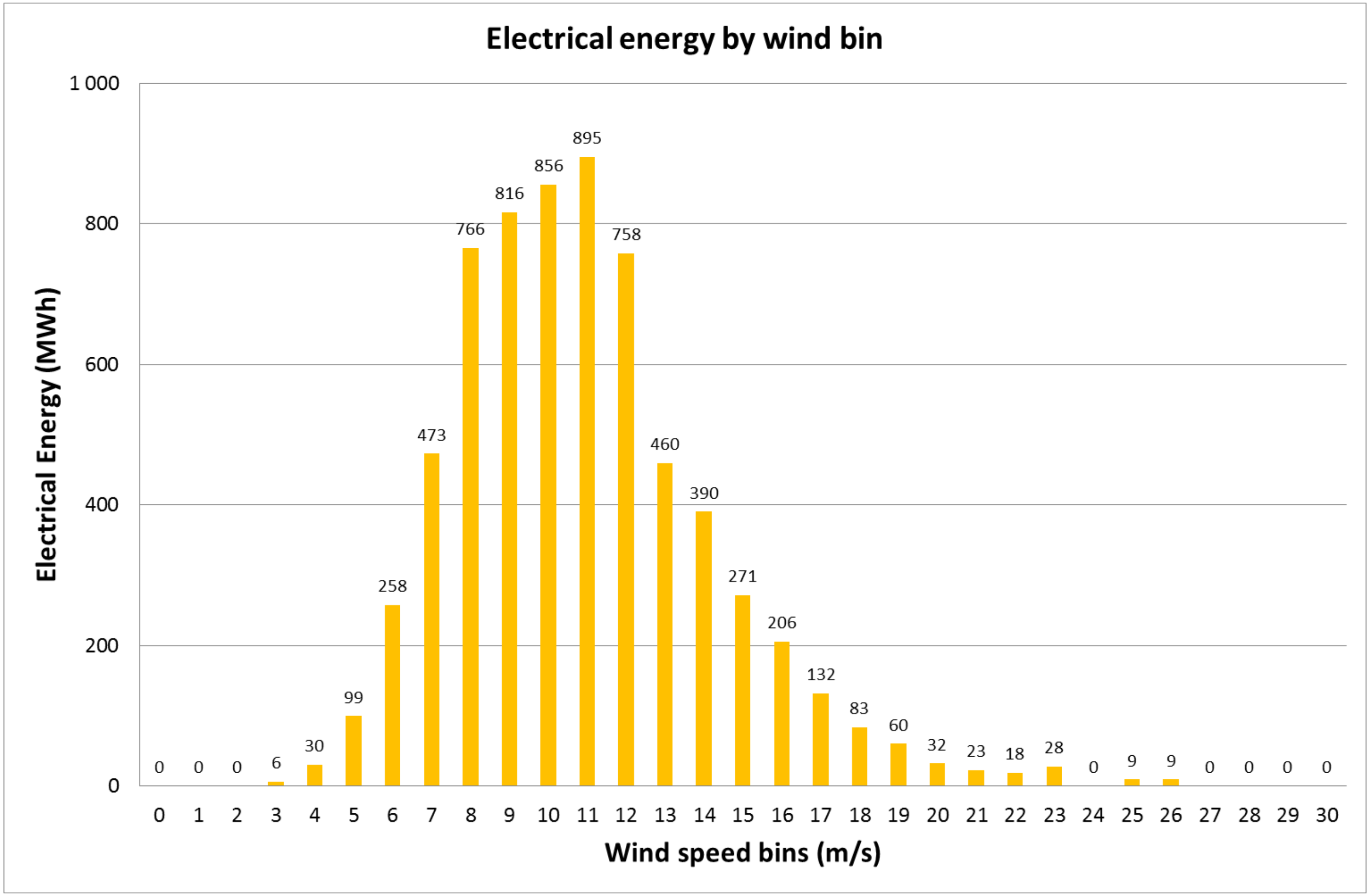
Experimental Computation – Input data



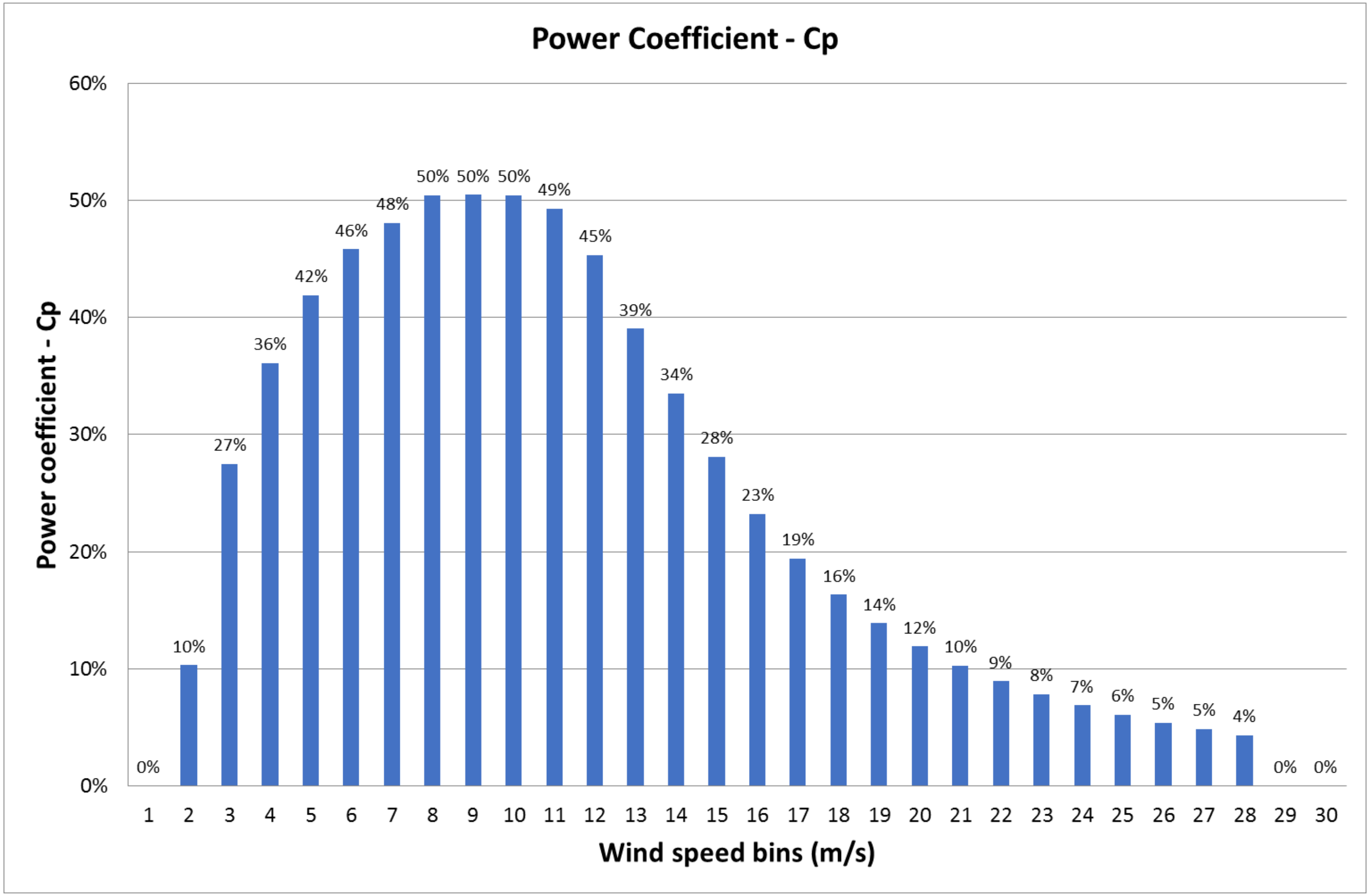
Experimental Computation – Input data



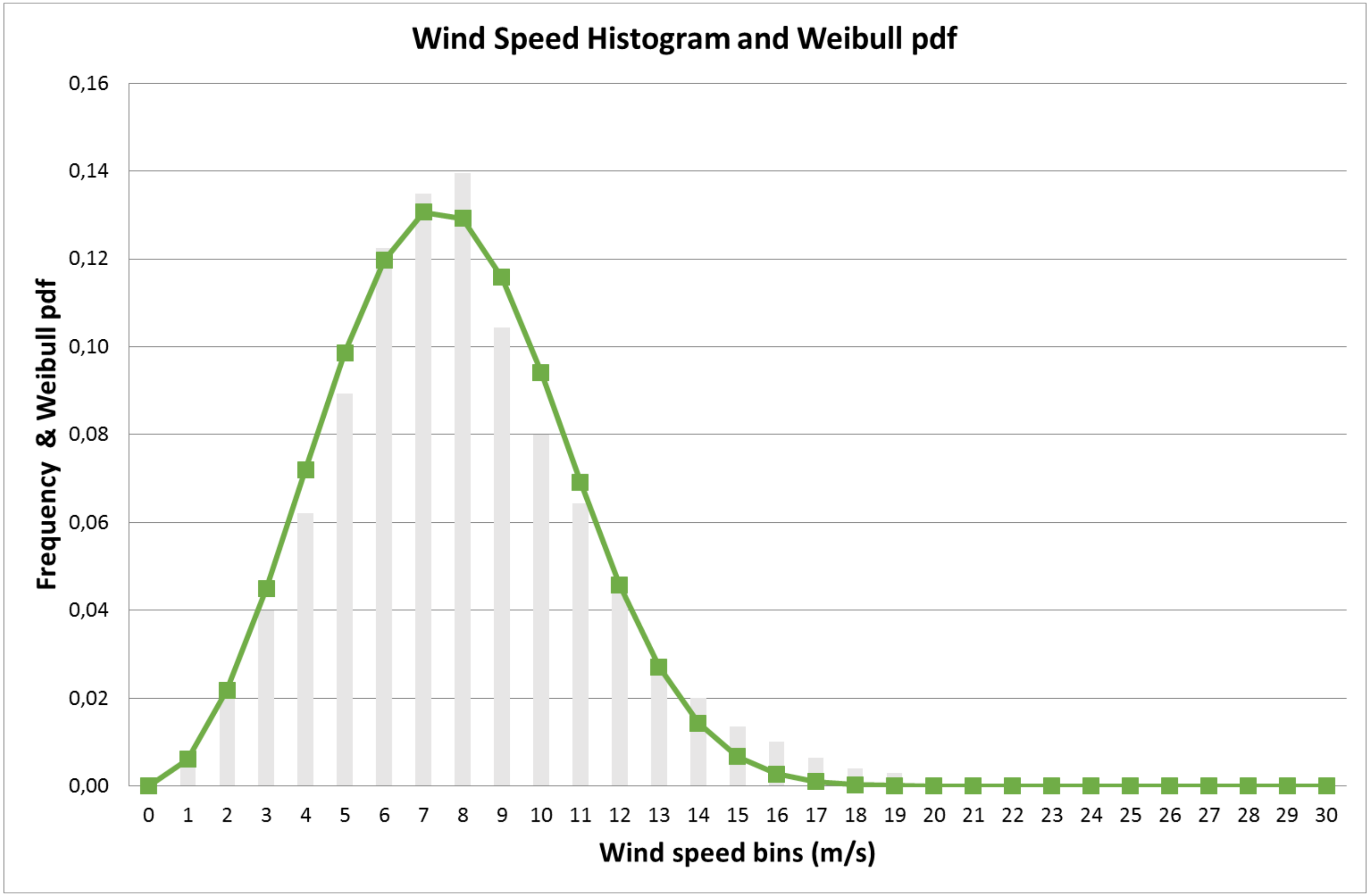
Experimental Computation – Results



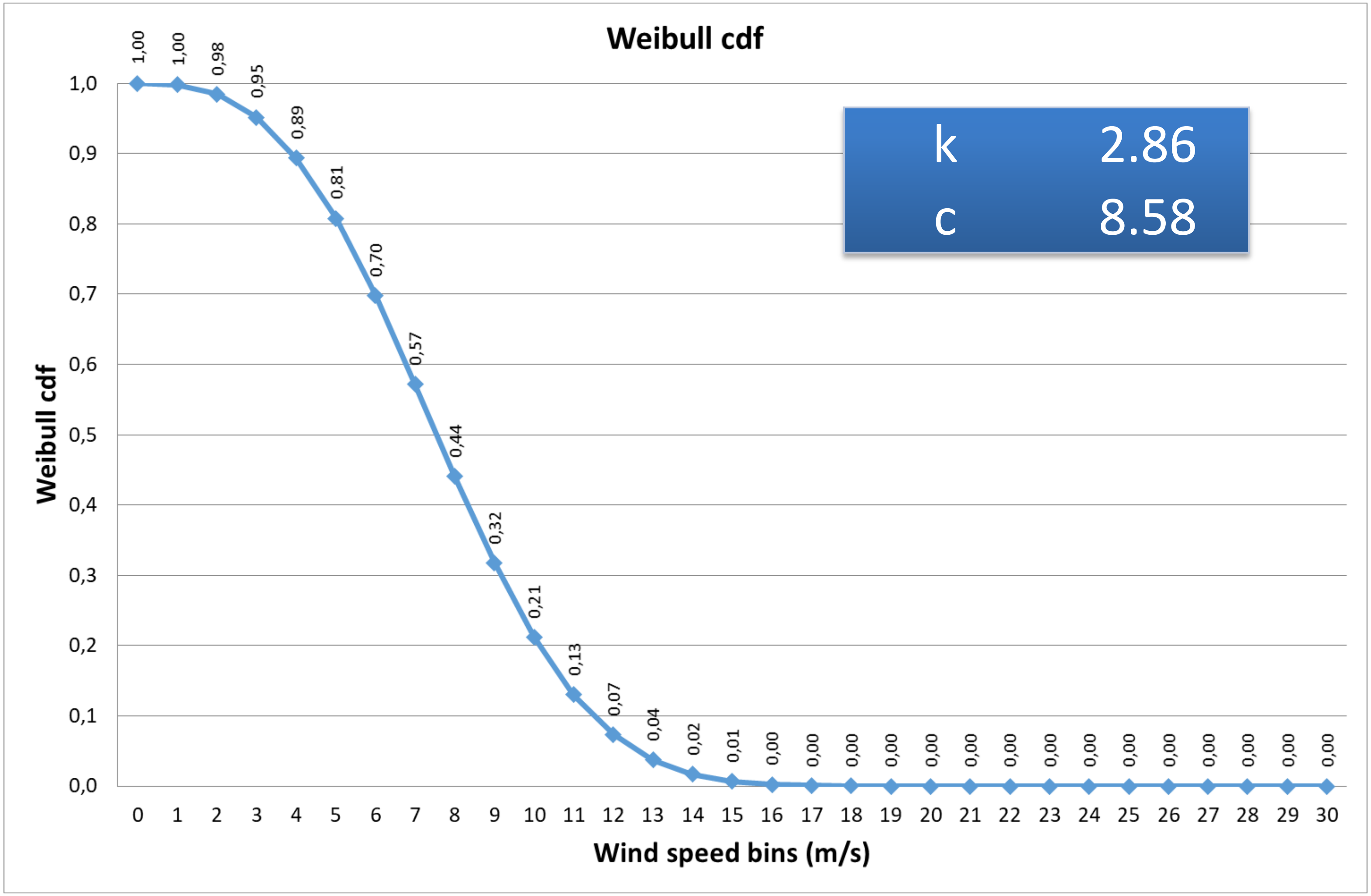
Experimental Computation – Results



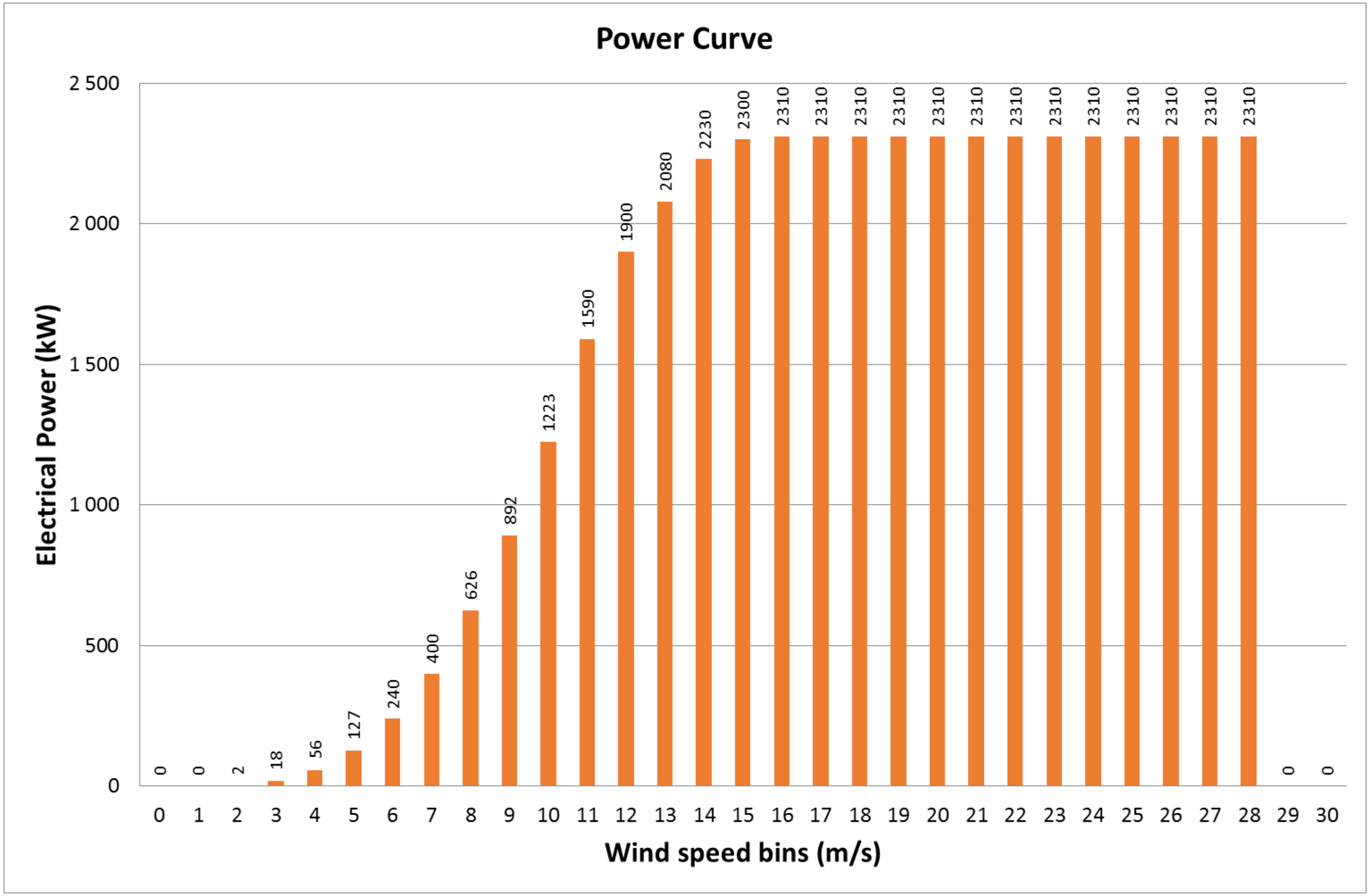
Analytical computation – Input data



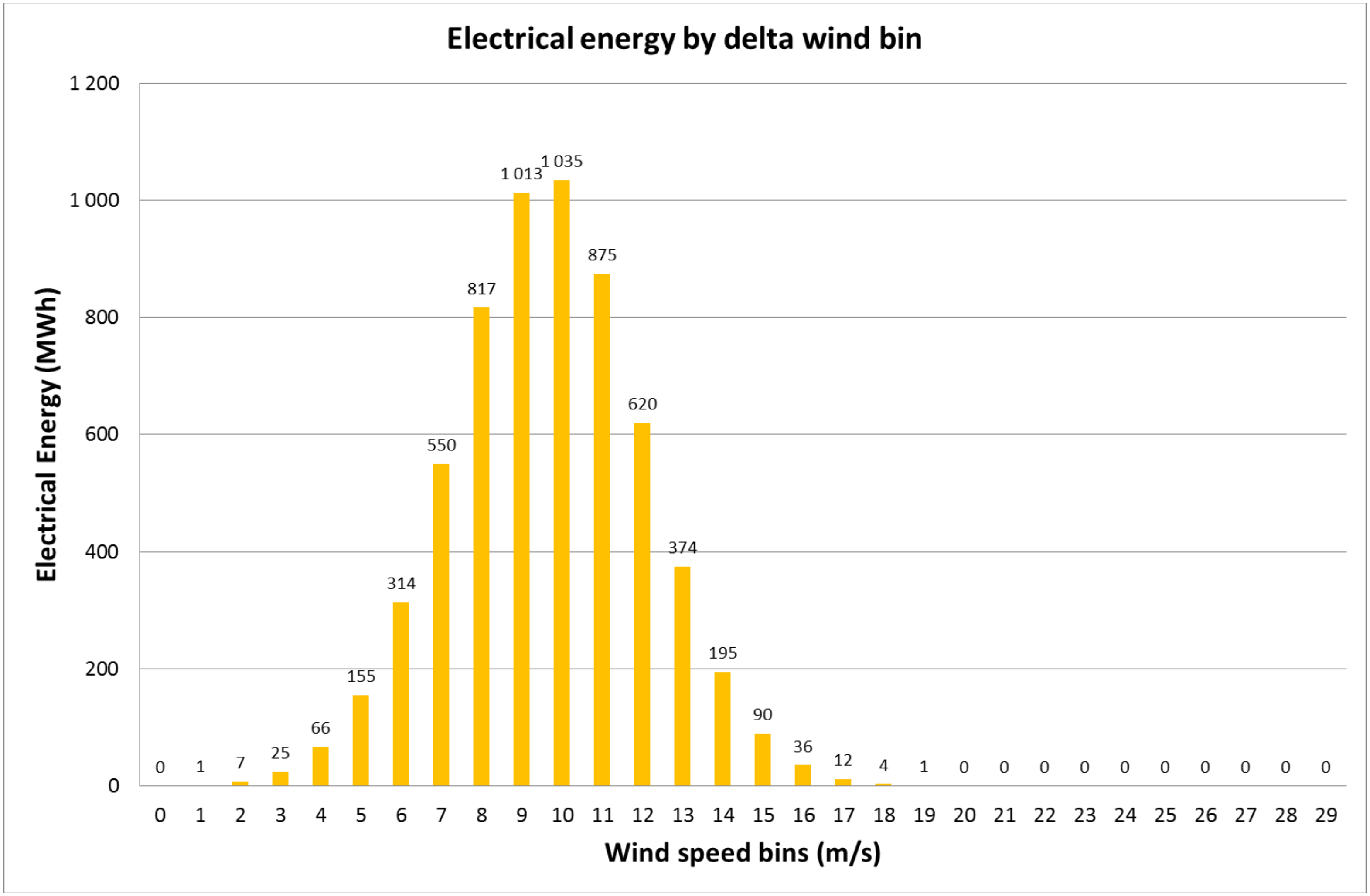
Analytic computation – Input data



Analytic Computation – Input data



Analytical Computation – Results



Results

	Experimental	Analytic
Swept area	3 959	3 959m2
Max. wind speed @hub	26.39	26.39m/s
Mean wind speed @hub	8.00	8.00m/s
Min. wind speed @hub	0.58	0.58m/s
Annual Energy	6 680	6 239MWh
Utilization factor	2 892	2 701h
Average power	763	712kW
Capacity factor	33.01%	30.83%

FE: 5327 MWh: error=-20%

ENERGY YIELD FAST ESTIMATE

Fast Estimate

$$\left(P_{avail}\right)_{avg} = \left(\frac{1}{2}\rho A u^3\right)_{avg} = \frac{1}{2}\rho A \left(u^3\right)_{avg}$$

$$\left(P_{avail}\right)_{avg} = \rho A \frac{3}{\pi} u_{ma}^3$$

$$E_a = P_{avg} 8760 \approx \left(C_p\right)_{avg} \left(P_{avail}\right)_{avg} 8760$$

$$\left(C_p\right)_{avg} \approx 0.25$$

$$\rho = 1.23 \text{ kg/m}^3$$

$$\frac{3}{\pi} \approx 0.95$$

$$E_a \approx 0.25 \rho A \frac{3}{\pi} u_{ma}^3 8760 \approx 0.3 A u_{ma}^3 8760$$

$$E_a = 2(RD)^2 u_{ma}^3 \quad \text{kWh}$$

Why $\left(u^3\right)_{avg} = \frac{6}{\pi} u_{ma}^3$?

$$\left(u^3\right)_{avg} = \int_0^\infty u^3 f_{Rayl}(u)\,du = \int_0^\infty u^3 \frac{2u}{c^2} \exp\left[-\left(\frac{u}{c}\right)^2\right] du = \frac{3}{4} c^3 \sqrt{\pi}$$

$$\left(u^3\right)_{avg} = \frac{3}{4}\sqrt{\pi}\left(\frac{2u_{ma}}{\sqrt{\pi}}\right)^3 = \frac{3}{4}\frac{8u_{ma}^3}{\pi} = \frac{6}{\pi}u_{ma}^3$$

$\mathrm{k} = 2$

$$\mathrm{u_{ma}} = \mathrm{c}\Gamma\left(1 + \frac{1}{\mathrm{k}}\right) = \mathrm{c}\frac{\sqrt{\pi}}{2}$$

$$\mathrm{f_{Weib}(u)} = \frac{\mathrm{k}}{\mathrm{c}}\left(\frac{\mathrm{u}}{\mathrm{c}}\right)^{\mathrm{k}-1} \exp\left[-\left(\frac{\mathrm{u}}{\mathrm{c}}\right)^{\mathrm{k}}\right]$$

$\mathrm{k} = 2$

$$\mathrm{f_{Rayl}(u)} = \frac{2}{\mathrm{c}}\frac{\mathrm{u}}{\mathrm{c}} \exp\left[-\left(\frac{\mathrm{u}}{\mathrm{c}}\right)^2\right]$$

Why $\frac{2}{c^2}\int_0^\infty u^4 \exp\left[-\left(\frac{u}{c}\right)^2\right]du = \frac{3}{4}c^3\sqrt{\pi}$?

$$\left(u^3\right)_{avg} = \int_0^\infty u^3 \frac{2u}{c^2}\exp\left[-\left(\frac{u}{c}\right)^2\right]du = \frac{2}{c^2}\int_0^\infty u^4 \exp\left[-\left(\frac{u}{c}\right)^2\right]du$$

From integral tables

$$\int_0^\infty x^m \exp\left(-ax^2\right)dx = \frac{\Gamma\left(\frac{m+1}{2}\right)}{2a^{\frac{m+1}{2}}}$$

$$m = 4;\ a = \frac{1}{c^2};\ \Gamma\left(\frac{5}{2}\right) = \frac{3}{2}\frac{\sqrt{\pi}}{2};\ a^{\frac{5}{2}} = \frac{1}{c^5}$$

$$\frac{2}{c^2}\int_0^\infty u^4 \exp\left[-\left(\frac{u}{c}\right)^2\right]du = \frac{2}{c^2}\frac{\frac{3}{4}\sqrt{\pi}}{\frac{2}{c^5}} = \frac{3}{4}c^3\sqrt{\pi}$$

Example

- WTG
  - Capacity = 660 kW; Sigmoid parameters: c_1=8.76 & c_2=1.48; Rated wind speed: 15 m/s; Rotor diameter = 47 m; Rotor height = 40 m; uma (40m) = 8.24 m/s
- Compute:
  - The electricity produced when the wind speed is comprised between 9 m/s and 11 m/s. Compare different methods.

Solution

$$P(u) = \left(\frac{660}{1 + \exp\left(-\frac{u - 8.76}{1.48} \right)} \right)$$

$$f(u) = \frac{\pi}{2} \frac{u}{8.24^2} \exp\left[-\frac{\pi}{4} \left(\frac{u}{8.24} \right)^2 \right]$$

$$F(u) = \exp\left[-\frac{\pi}{4} \left(\frac{u}{8.24} \right)^2 \right]$$

Method#1

$$E(9 < u < 11) = 8760 \int_9^{11} P(u) f(u) du = 578.20\text{MWh} \quad (\text{step} = 0.01\text{m/s})$$

Method#2: error=-0.7%

$$E(9 < u < 11) = 8760 \left[(F(9) - F(10)) \left(\frac{P(9) + P(10)}{2} \right) + (F(10) - F(11)) \left(\frac{P(10) + P(11)}{2} \right) \right] = 574.34\text{MWh}$$

Method#3: error=-1.4%

$$g(u) = P(u) f(u)$$

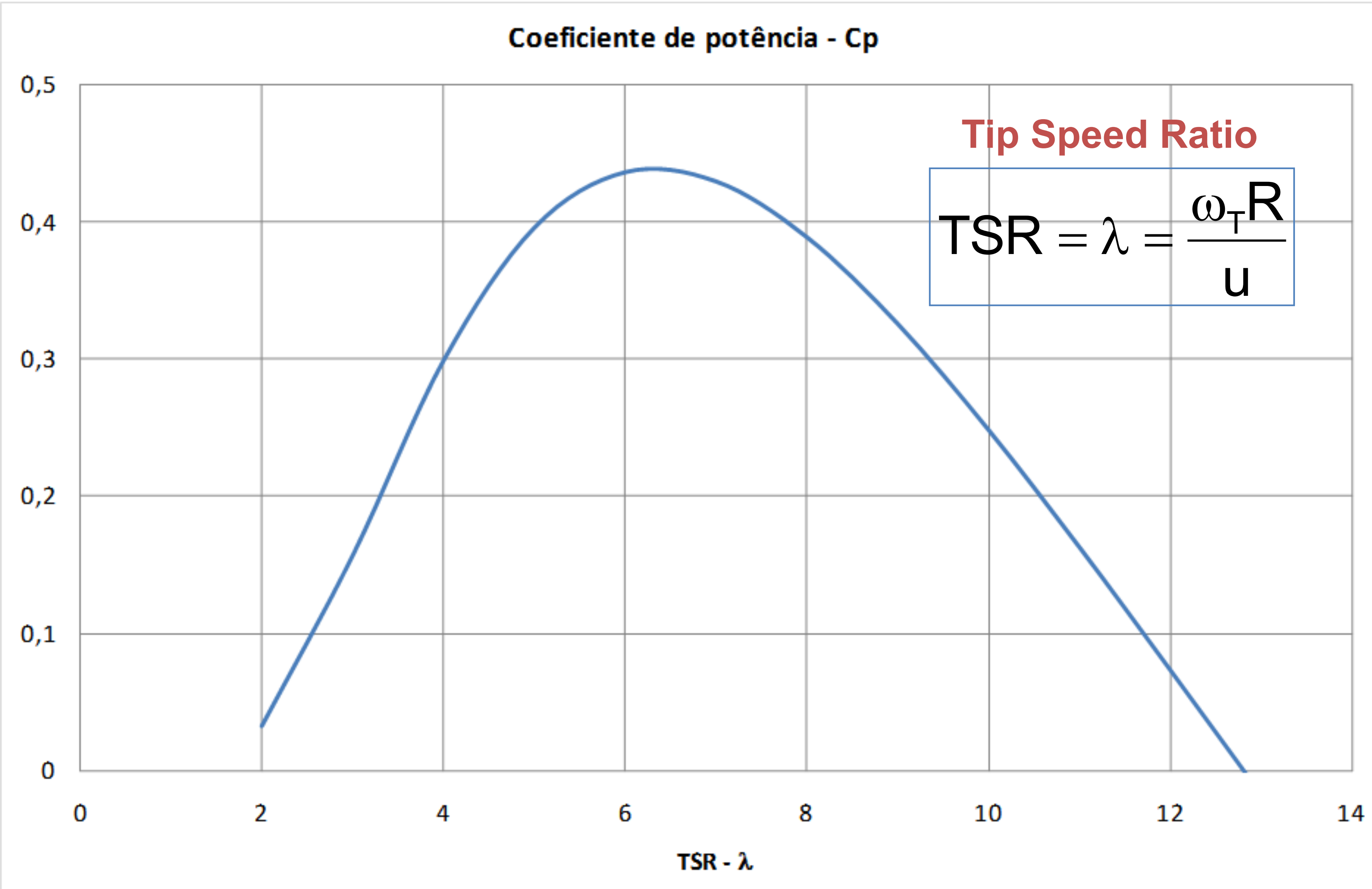
$$E(9 < u < 11) = 8760 \left[\left(\frac{g(9) + g(10)}{2} \right) + \left(\frac{g(10) + g(11)}{2} \right) \right] = 569.83\text{MWh}$$

Method#4: error=46%

$$E(9 < u < 11) = 8760 (g(9) + g(10) + g(11)) = 8760 (P(9) f(9) + P(10) f(10) + P(11) f(11)) = 846.02\text{MWh}$$

THE NEED FOR VARIABLE SPEED

Tip Speed Ratio

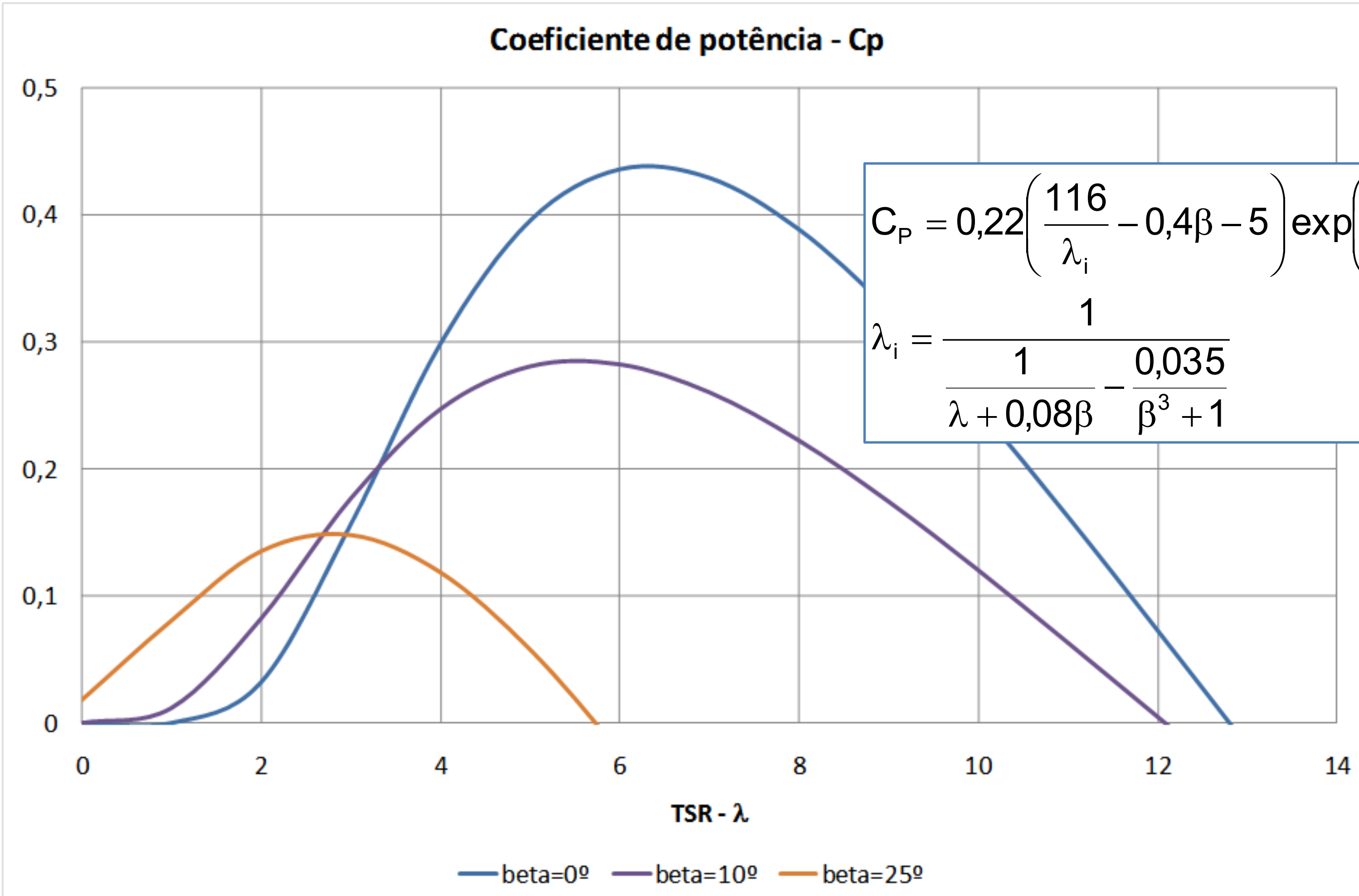


POWER CONTROL

Pitch control

Pitching changes the angle of attack α and hence the power coefficient C_p

Pitch control

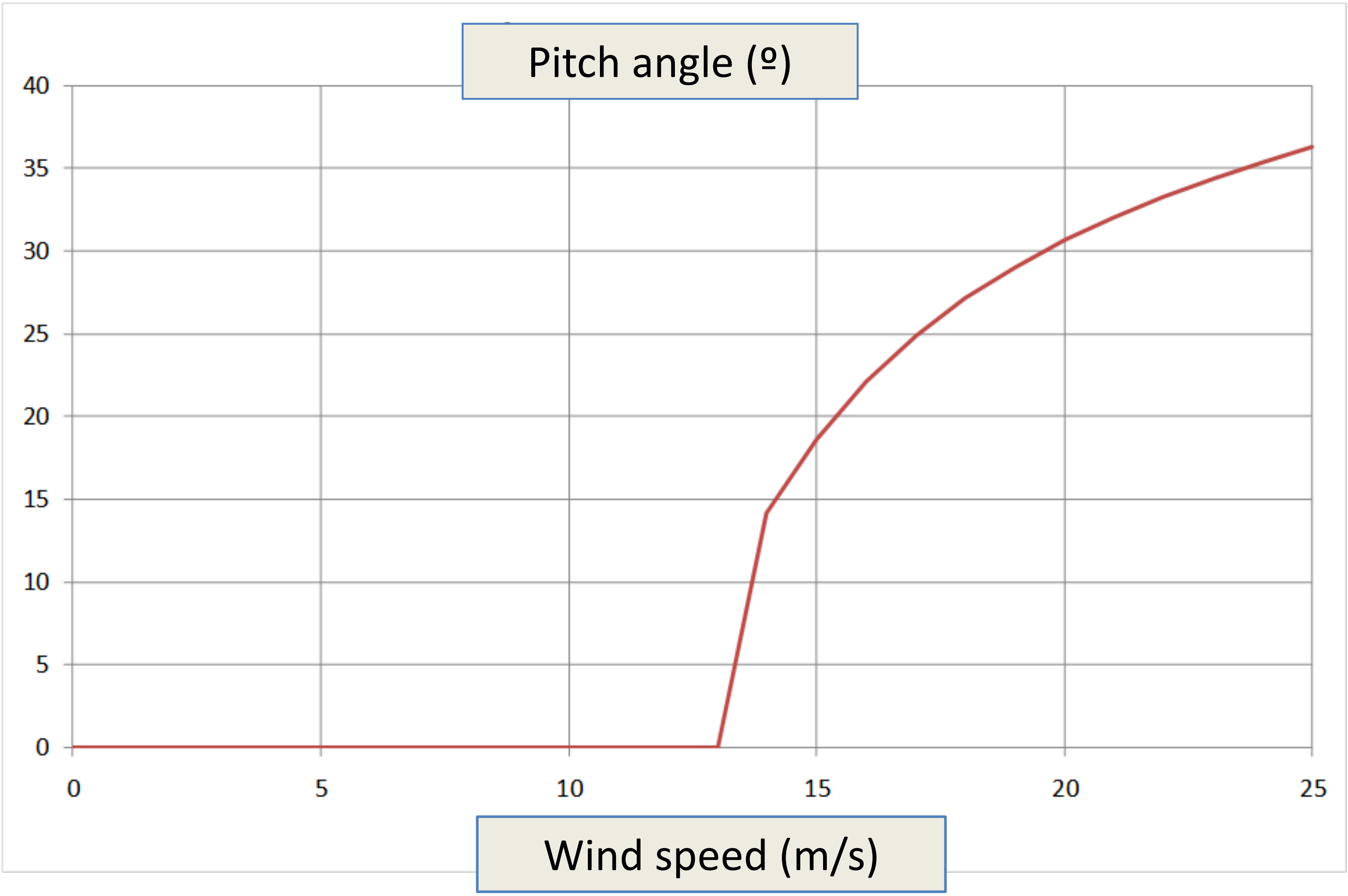


$$C_P = 0{,}22\left(\frac{116}{\lambda_i} - 0{,}4\beta - 5\right)\exp\left(-\frac{12{,}5}{\lambda_i}\right)$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0{,}08\beta} - \frac{0{,}035}{\beta^3 + 1}}$$

Cp reduces with pitch angle increase

Pitch control



Between cut in wind speed and nominal wind speed, the pitch is regulated (normally at zero value) in order to maximize C_p
Between nominal wind speed and cut off wind speed is increased in order to control (limit) power

WIND ENERGY CONVERSION EQUIPMENT

Electrical generators – Type#1 and #2

- **Squirrel-Cage Induction Generators (SCIG) – Type#1**
  - Used in the first WTG to keep costs down and reliability high
  - Very narrow rotor speed variation (slip) -> poor efficiency
  - Need capacitors to compensate the reactive power
  - Not used anymore

- **Wound-Rotor Induction Generator – Type#2**
  - Higher rotor speed variation -> increase efficiency
  - Wound-rotor induction generator connected through slip rings to thyristor-controlled variable resistances
  - Need capacitors to compensate the reactive power
  - Not used anymore

Electrical generators – Type#3

- **Double Fed Induction Generator (DFIG) – Type#3**
  - AKA Double Output Induction Generator (DOIG)
  - Take the Type#2 design to the next level, by adding variable frequency ac excitation (instead of simply resistance) to the rotor
  - Wound rotor with double output (rotor and stator) and electronic interface in the rotor with 2 converters
  - The 2 converters allow a bi-directional power flow in the rotor and a much wider speed range, above and below synchronous speed
  - The set of converters are typically only 30% of the rating of the machine
  - Can control voltage by consuming or generating reactive power
  - It is the most popular technology around the world

Electrical generators – Type#4

- **Direct Driven DC-Link Synchronous Generator (DDSG) – Type#4**
  - Synchronous generator (alternator) with rectifier and inverter
  - The output of the generator is sent to the grid through a full-scale back-to-back frequency converter
  - No gearbox -> much wider speed range
  - Electrically Excited Synchronous Generators (EESG), or self-excited Permanent Magnet Synchronous Generators (PMSG)
  - Can control voltage by consuming or generating reactive power
  - Highly efficient WTG