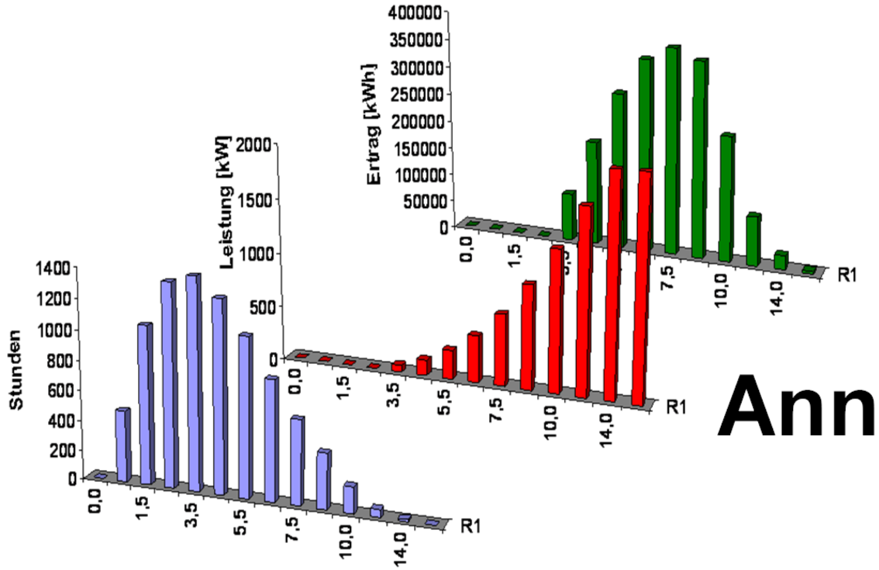
Design of wind turbine systems
SS 2016



Tutorial 1:
AEP –
Annual Energy Production

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ForWind – Wind Energy Systems

The partial use of lecture material developed at SWE - University of Stuttgart is acknowledged.

Objective and motivation

For economical reasons it is important to maximize the annual energy production (AEP) of wind turbines.

- The AEP depends on the wind turbine and the site
- Three options are possible:

  - chose a windier site or increase the hub height

  - increase the rotor diameter

  - increase the rated power
- Reference turbine

  - P_{rated} = 2 MW

  - D = 80 m

  - H_{hub} = 65 m

Fig. http://www.exchange3d.com

Wind turbine: the power curve

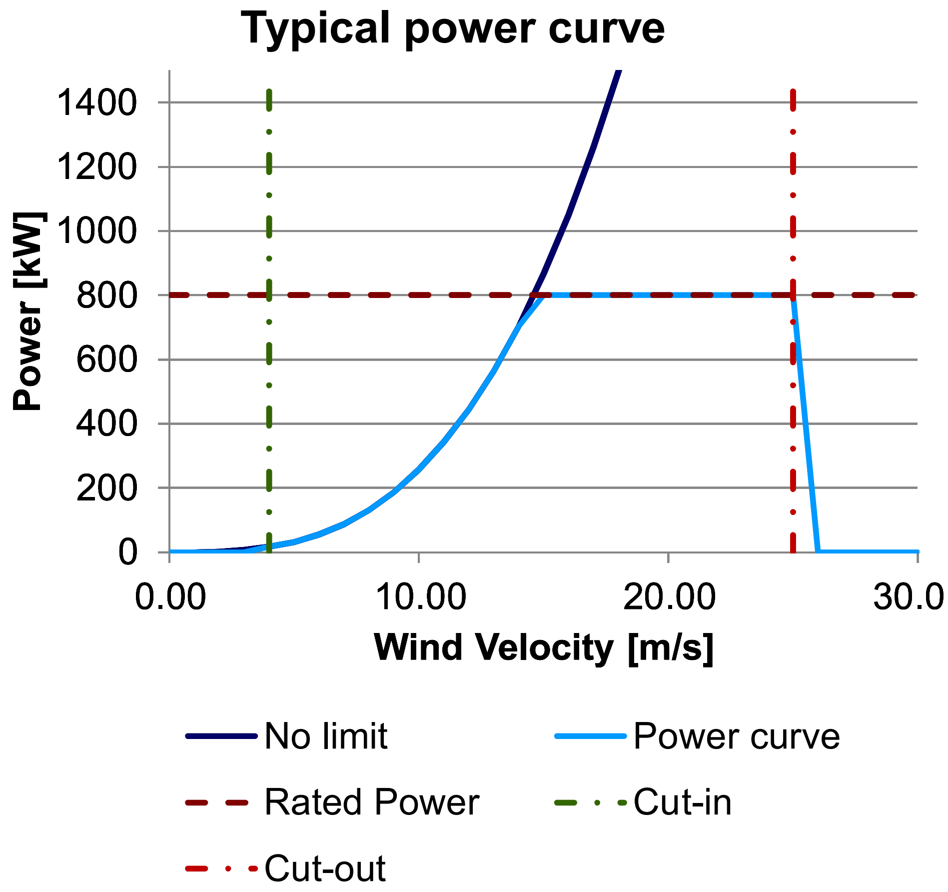
Defines the relation between the power output and the wind speed.

- Power proportional to the cube of the wind velocity and to the rotor swept area

$$P \propto u^3 \left(\frac{D}{2}\right)^2$$

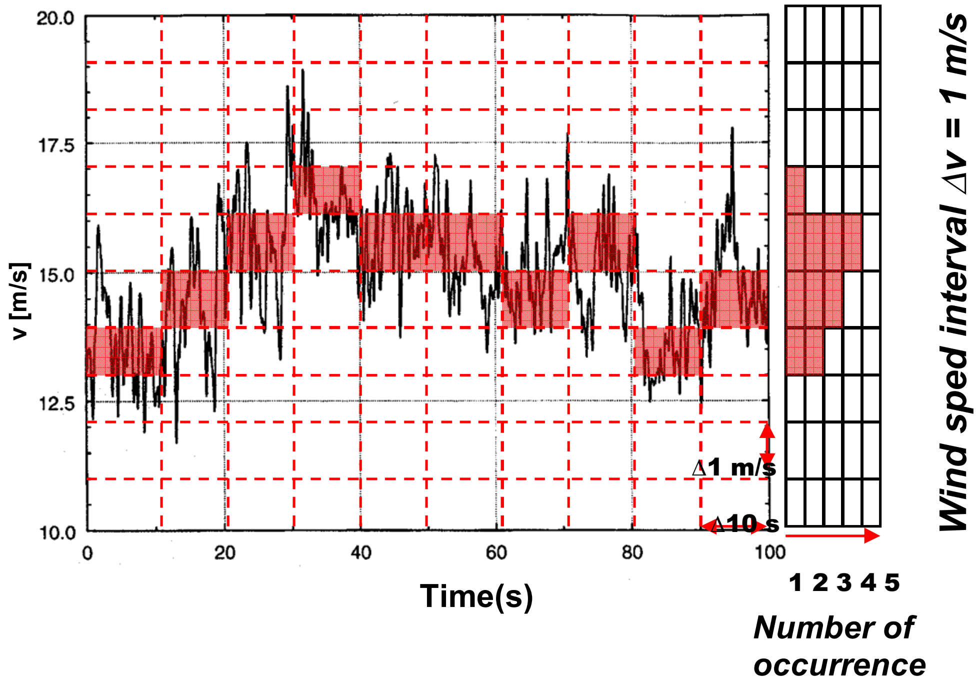
- Upper limit: rated power (defines also the rated wind velocity, typical values within11-12 m/s)

- Left/right limits: cut-in/out velocity (typical values are 3.5-4/25-30 m/s)

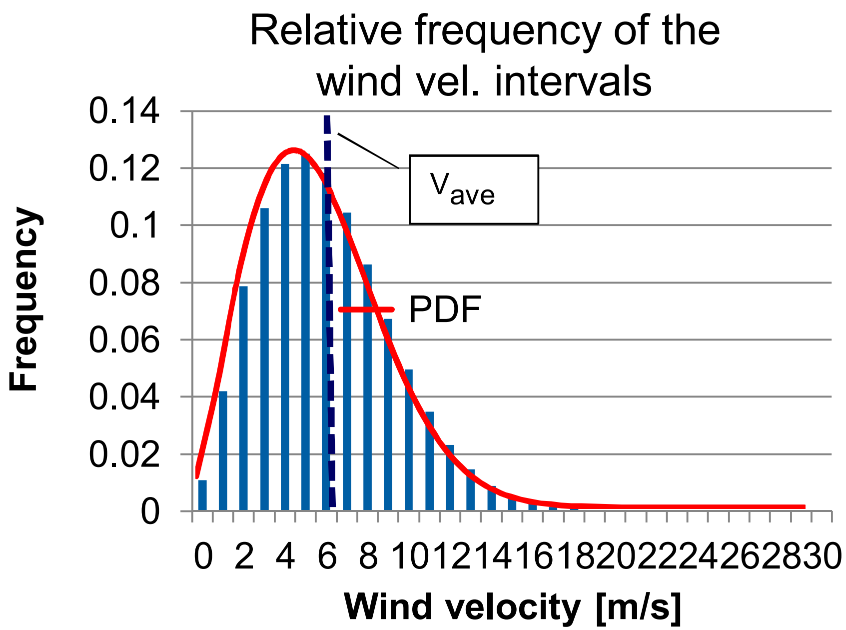


Site: the wind distribution

The AEP is based on the annual distribution of the wind speed (10 min. average).



1. Ten minutes statistics of the experimental data
2. Wind speed range binning
3. Bin occurrence count
4. Wind speed probability density function evaluation from the relative frequency of the bins



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Calculation of gross annual energy yield

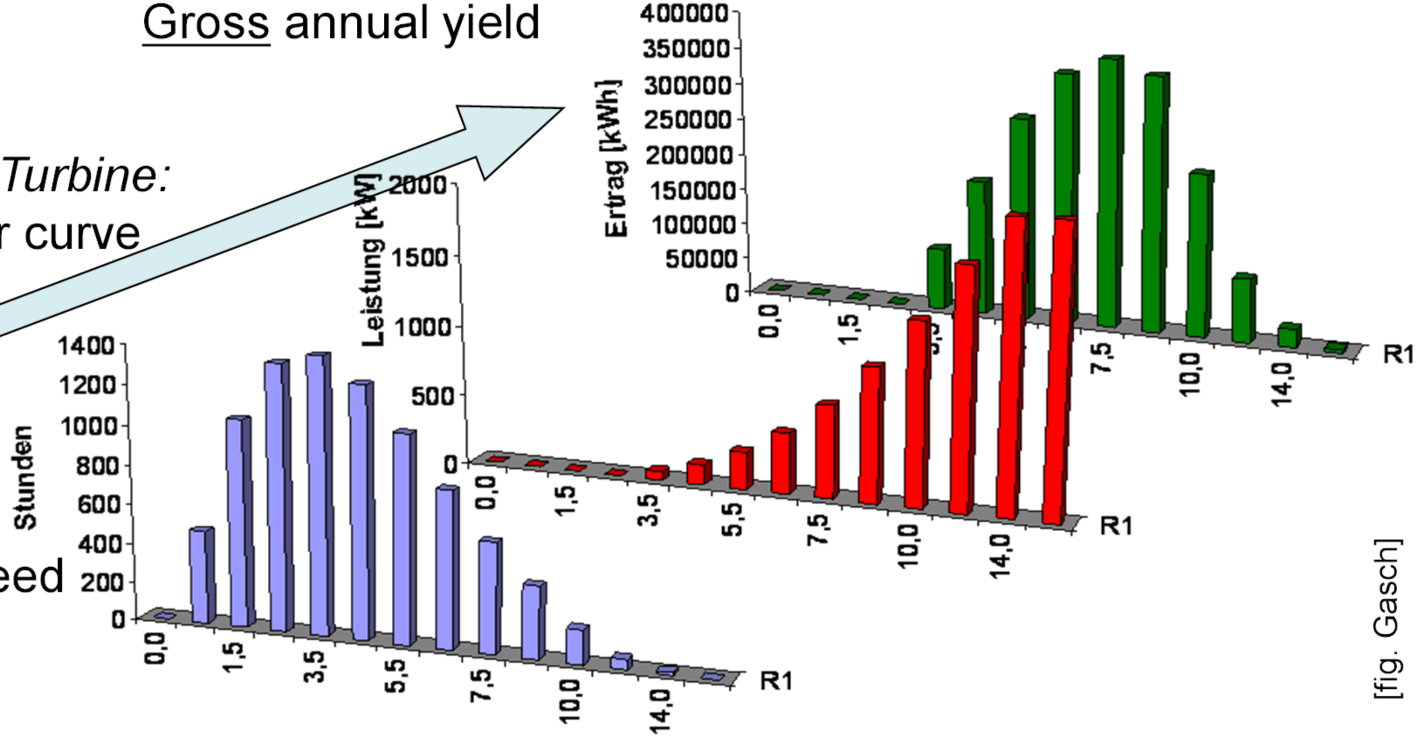
$$E_{total} = \Sigma\, E_i = \Sigma\, T\, h_i\, P_i$$

hi class frequency ti/T
Pi :power output of the class
T : given time period
Ei yield of the class

Site & Turbine:
Gross annual yield

Wind Turbine:
Power curve

Site:
Histogram or
(Weibull- or Rayleigh-)
Distribution of wind speed



[fig. Gasch]

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„Capacity factor“ and „Full load hours“

The “Full load hours” and the “Capacity factor” define:

- the goodness of a site
- how good a wind turbine fits a site

$$\textbf{Full load hours} = \frac{\textbf{actual AEP [kWh]}}{\textbf{rated power [kW]}}$$

$$\textbf{Capacity factor} = \frac{\textbf{actual AEP [kWh]}}{\textbf{rated power [kW]} \bullet \textbf{8760 h}}$$

- Capacity factor: 20 - 70% , usually 25 - 30%

To evaluate the actual AEP
- all the loss sources and
- the effective operating hours
should be considered.

Class assignment

Exercise 1

To enlarge the AEP and therefore have more economical benefits, consider and compare three options A,B,C. In each option one of the three parameter v_{ave}, P_{rated} and D is 10% enlarged compared to the reference case.

In slides #9 to #12 identify the changed parameter and fill in the gaps as well as the table on slide #8 with the missing values.

Exercise 2

a) Identify which case (reference, options A, B and C) the AEP distributions on the slides from #13 to #16 are related to.

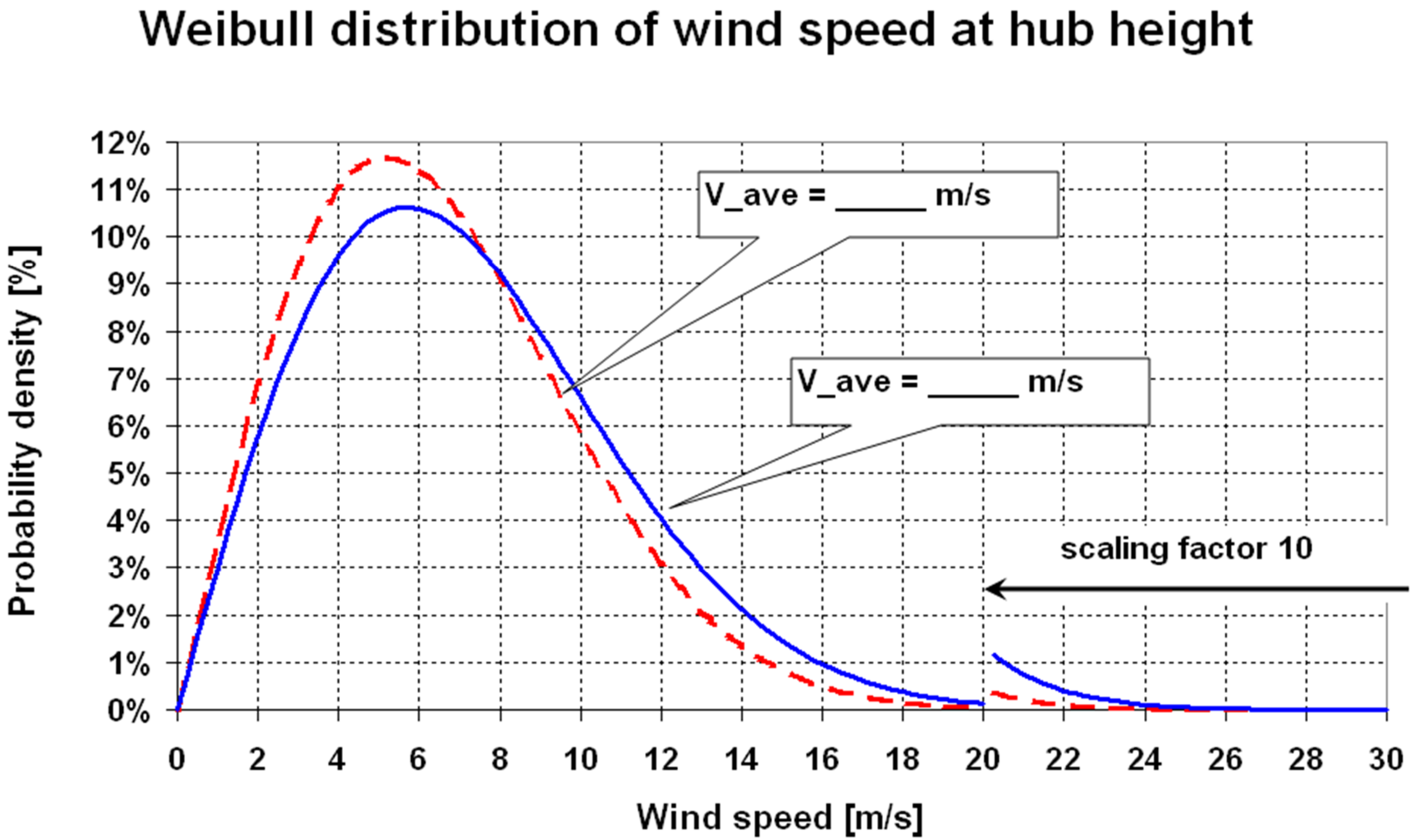
b) Calculate the full load hours and capacity factor

To compute the actual AEP consider 98% availability, 3% grid-connection losses and 10% contingency reduction.

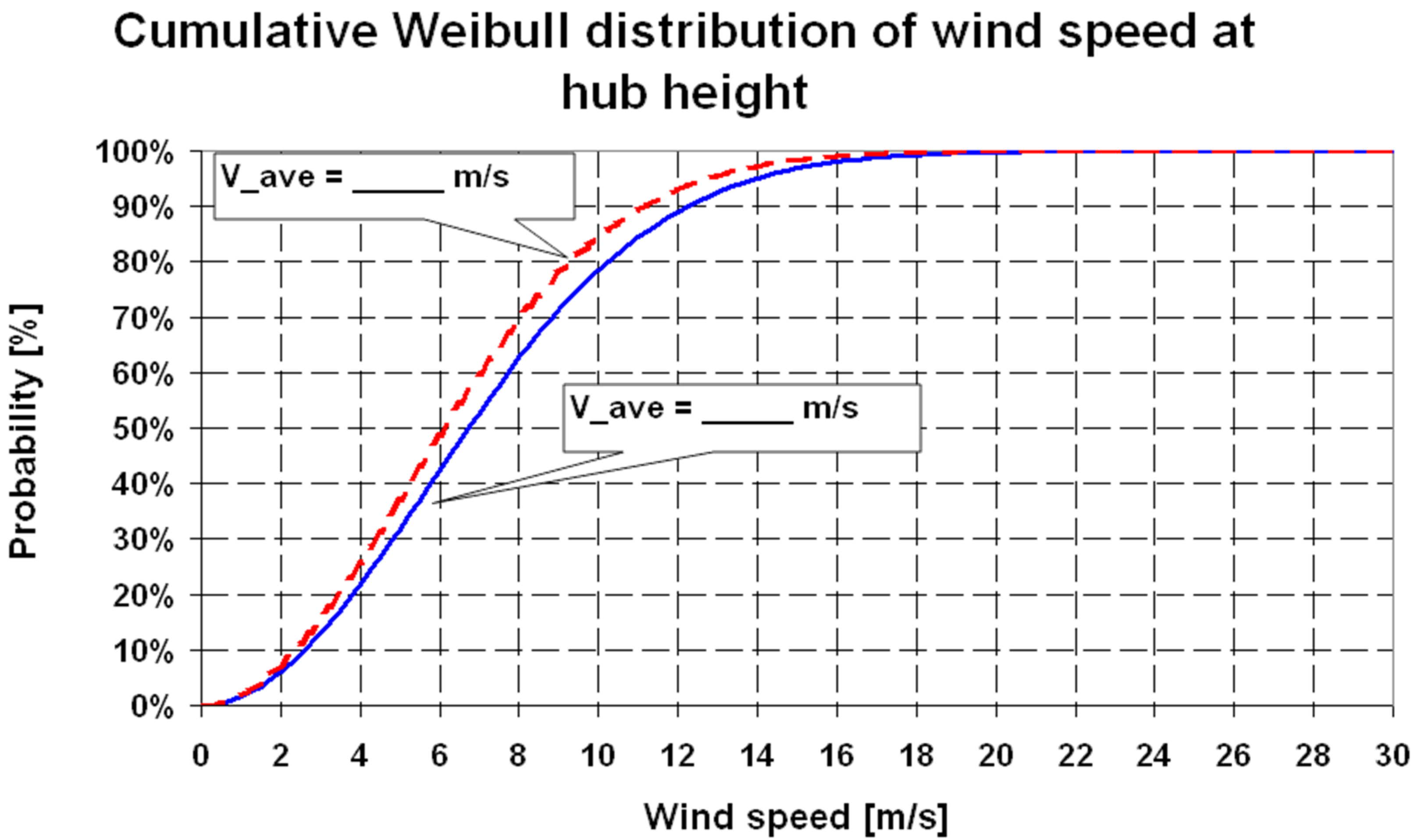
Comparison of the options

	Reference Case	Option A	Option B	Option C
Annual average wind velocity, v_{ave}	6,5			
Rated power, P	2000 kW			
Rotor diameter, D	80 m			
Specific rating				
Gross Annual Energy Production, AEP				
Relative AEP	100 %			

Option A: different annual wind distribution



Option A: different annual wind distribution

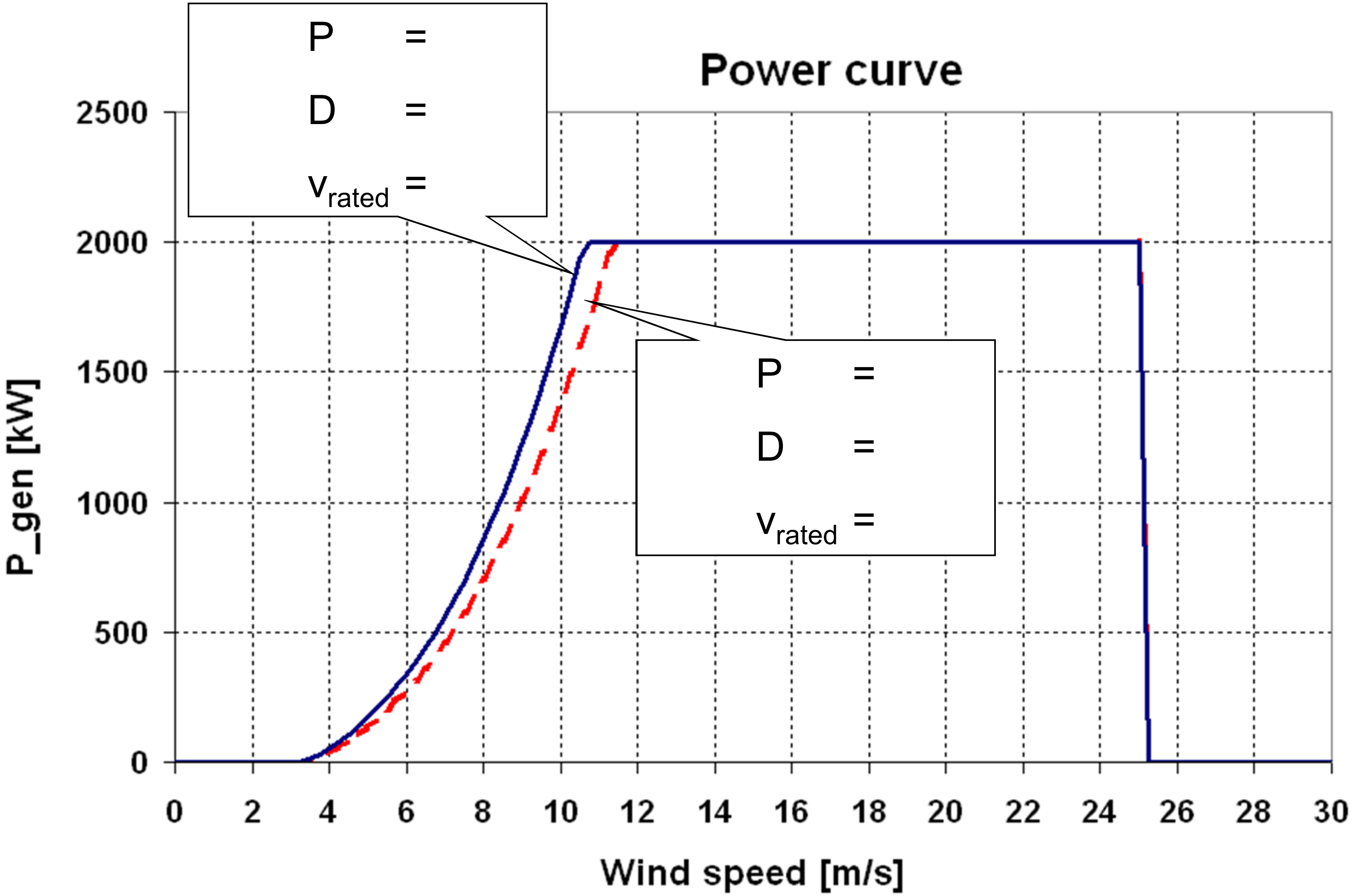


Questions:

a) What is the probability that the wind speed is below the cut-in value in the reference case?

b) What is the probability that the wind overtakes the rated wind velocity in the reference case?

Option B: different wind turbines



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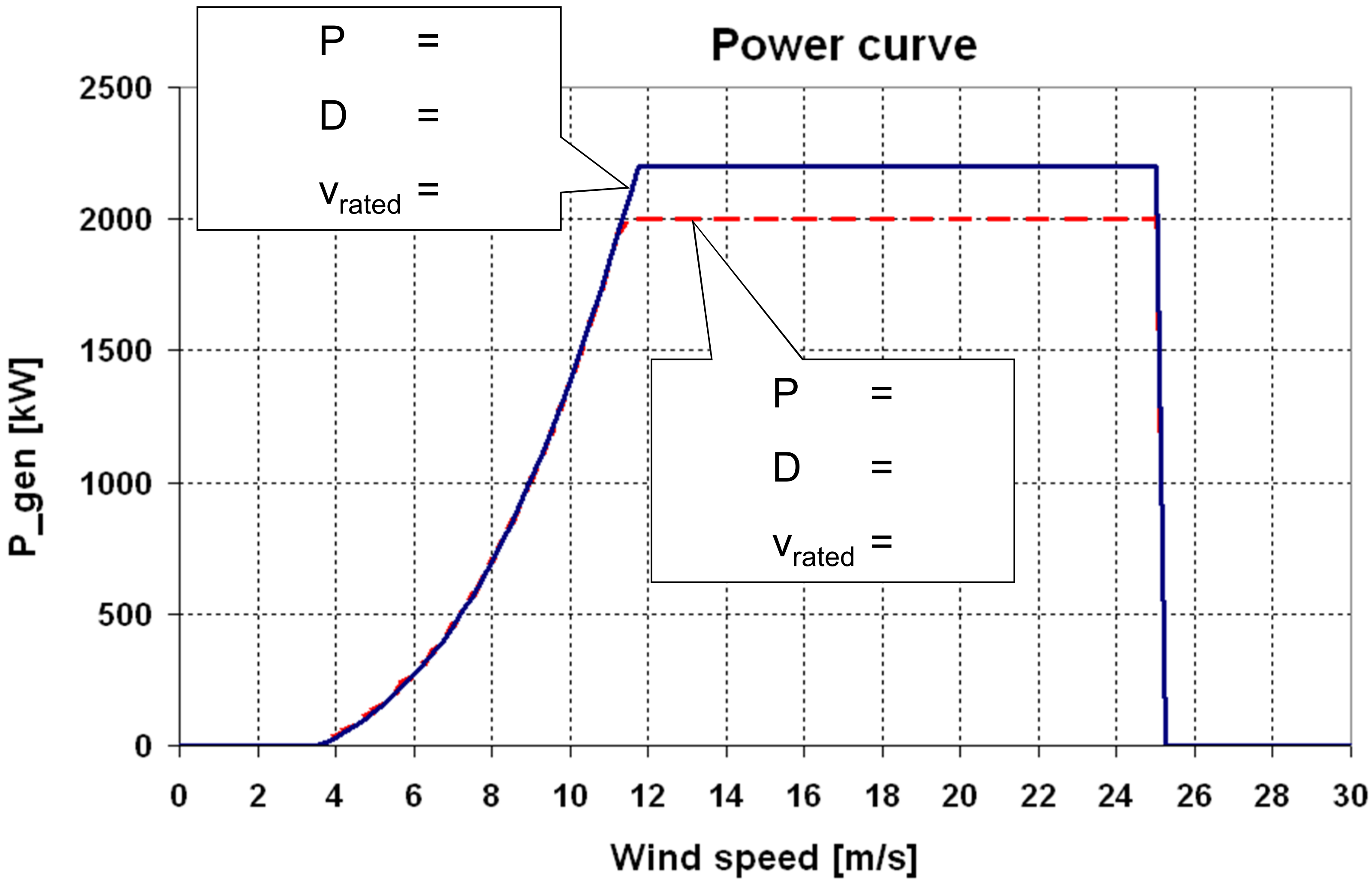
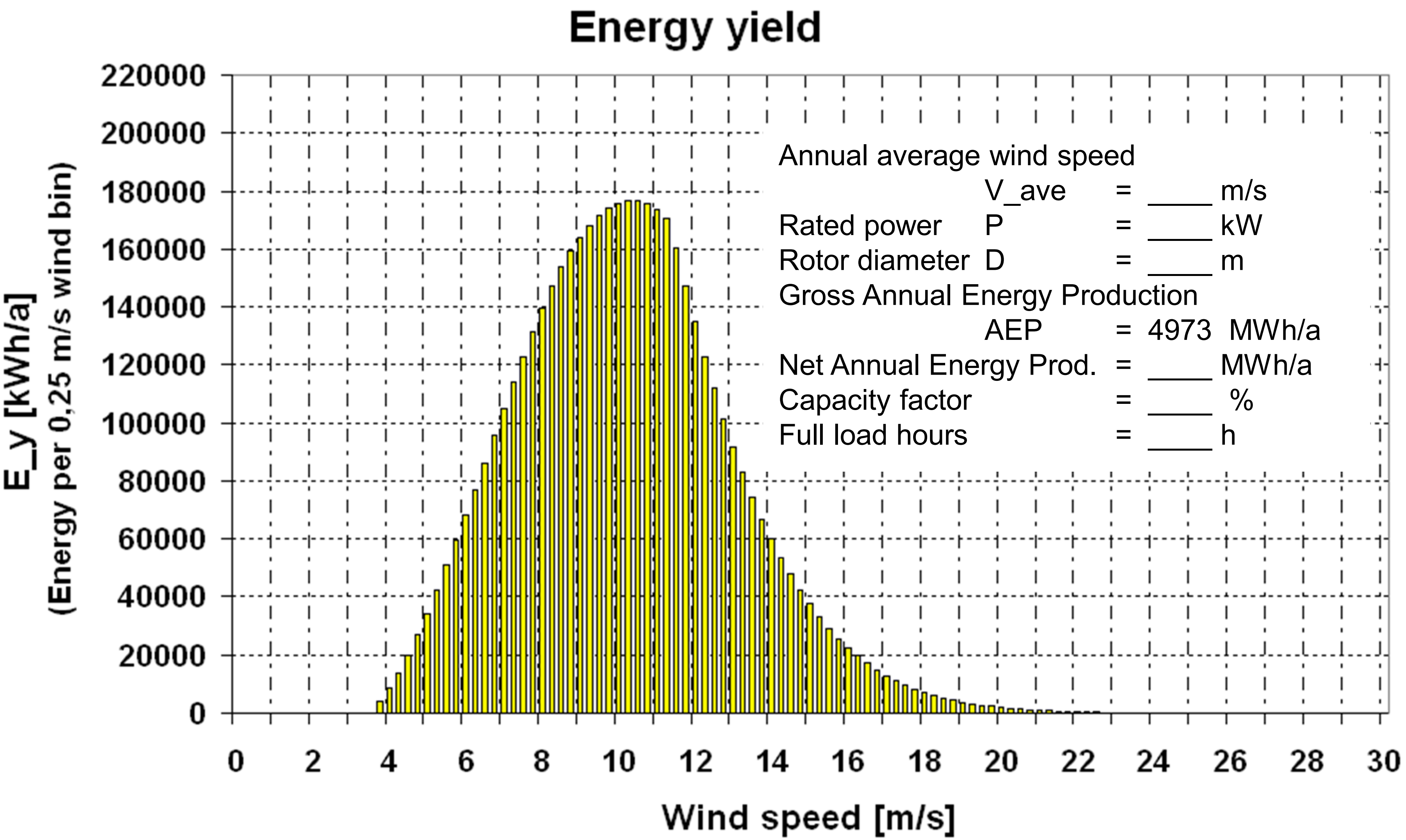
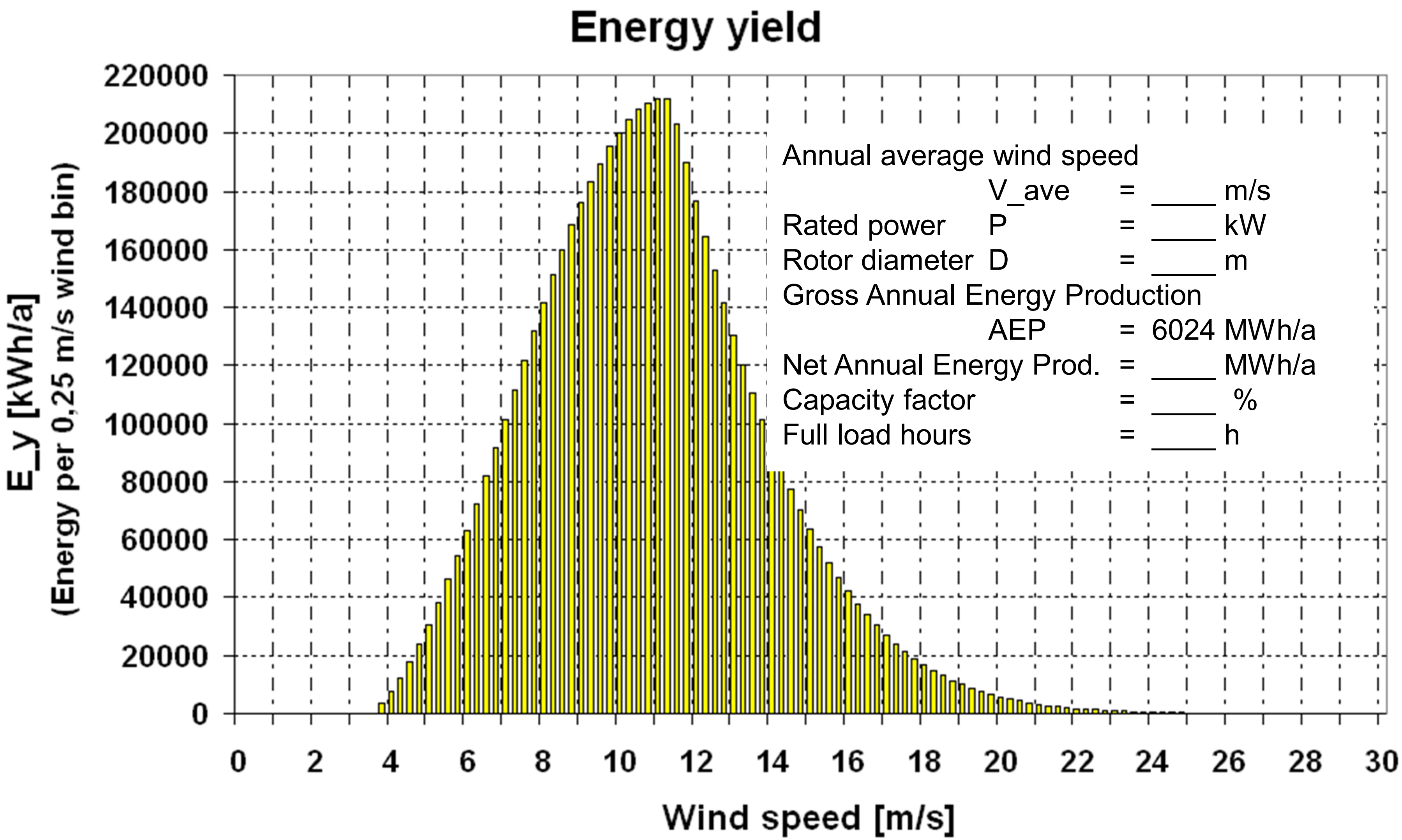
Option C: different wind turbines



Option __

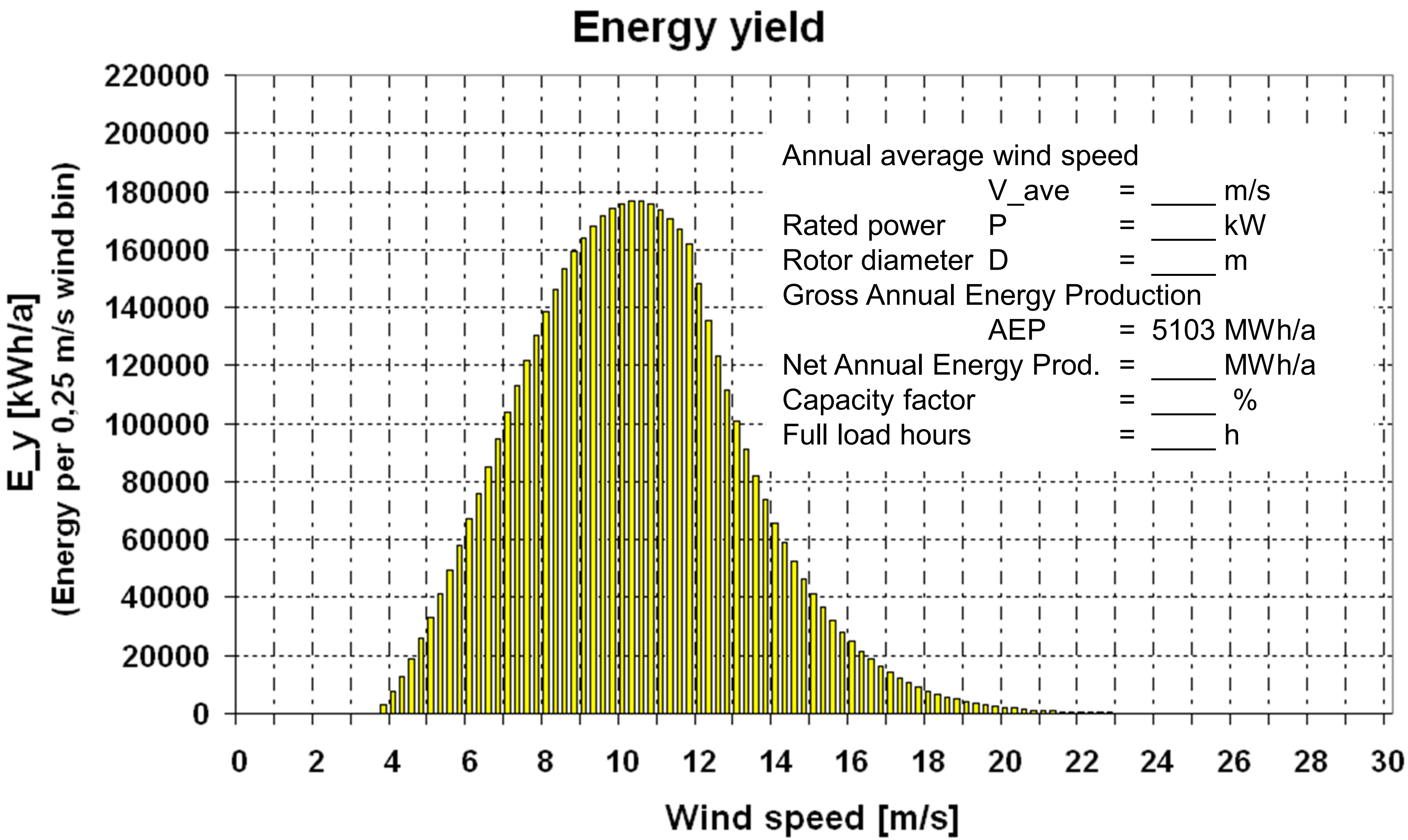

Energy yield
E_y [kWh/a]
(Energy per 0,25 m/s wind bin)
220000
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Wind speed [m/s]
Annual average wind speed
V_ave = _____ m/s
Rated power P = _____ kW
Rotor diameter D = _____ m
Gross Annual Energy Production
AEP = 4973 MWh/a
Net Annual Energy Prod. = _____ MWh/a
Capacity factor = _____ %
Full load hours = _____ h

Option __



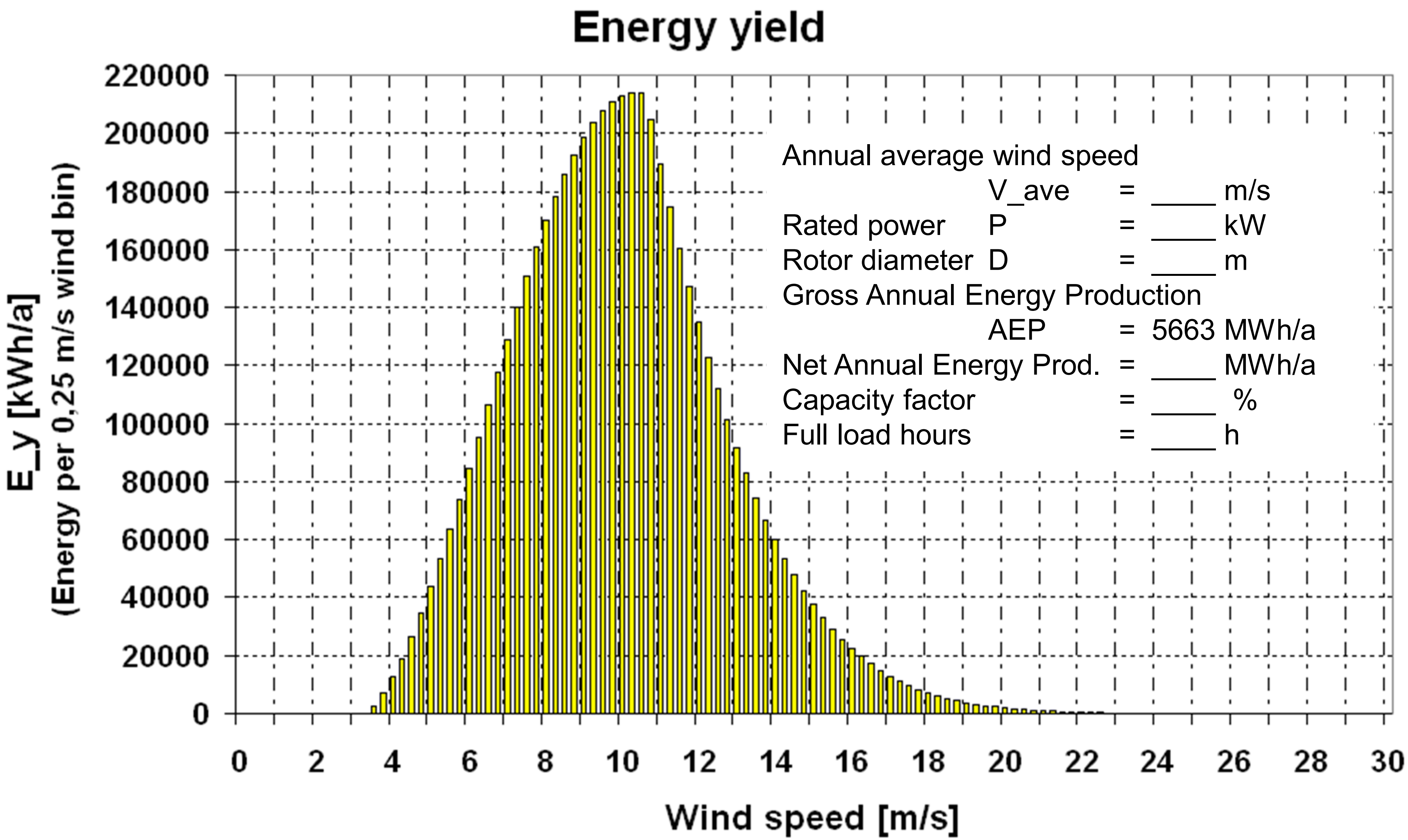
Energy yield
E_y [kWh/a]
(Energy per 0,25 m/s wind bin)
220000
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Wind speed [m/s]
Annual average wind speed
V_ave = ____ m/s
Rated power P = ____ kW
Rotor diameter D = ____ m
Gross Annual Energy Production
AEP = 6024 MWh/a
Net Annual Energy Prod. = ____ MWh/a
Capacity factor = ____ %
Full load hours = ____ h

Option __

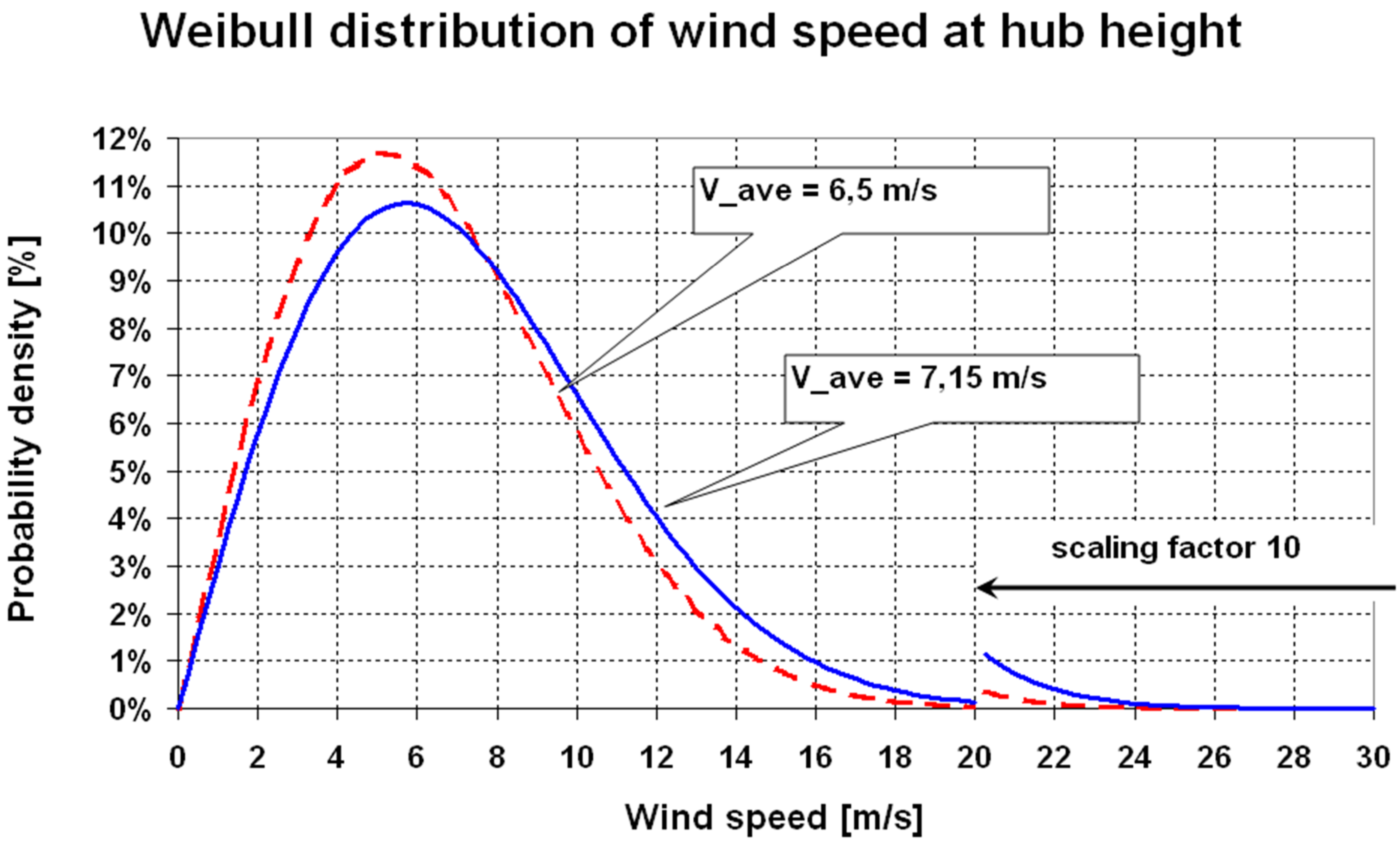


Energy yield
220000
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
E_y [kWh/a]
(Energy per 0,25 m/s wind bin)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Wind speed [m/s]
Annual average wind speed
V_ave = ____ m/s
Rated power P = ____ kW
Rotor diameter D = ____ m
Gross Annual Energy Production
AEP = 5103 MWh/a
Net Annual Energy Prod. = ____ MWh/a
Capacity factor = ____ %
Full load hours = ____ h

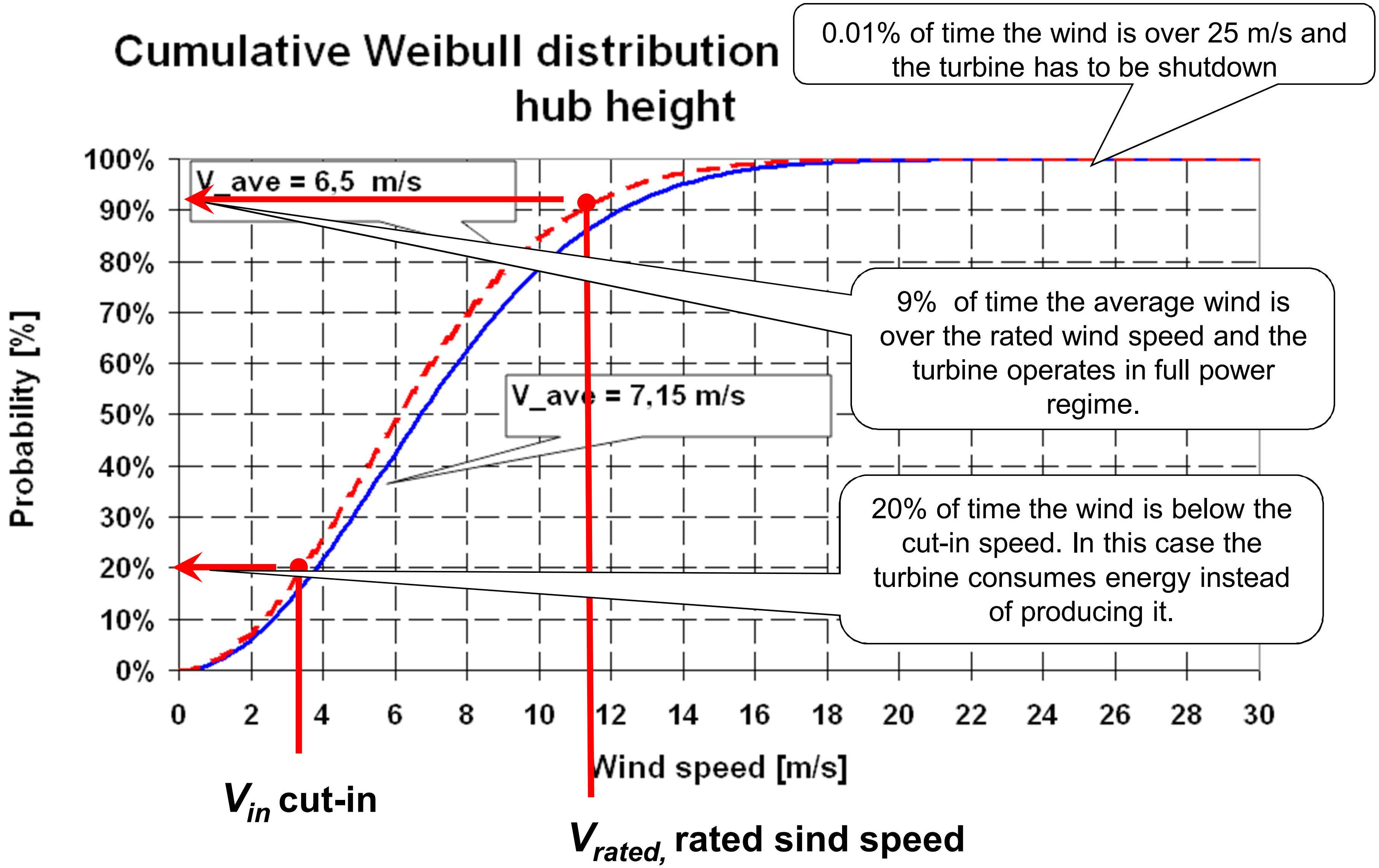
Option __


Energy yield
E_y [kWh/a]
(Energy per 0,25 m/s wind bin)
220000
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Wind speed [m/s]
Annual average wind speed
V_ave = ____ m/s
Rated power P = ____ kW
Rotor diameter D = ____ m
Gross Annual Energy Production
AEP = 5663 MWh/a
Net Annual Energy Prod. = ____ MWh/a
Capacity factor = ____ %
Full load hours = ____ h

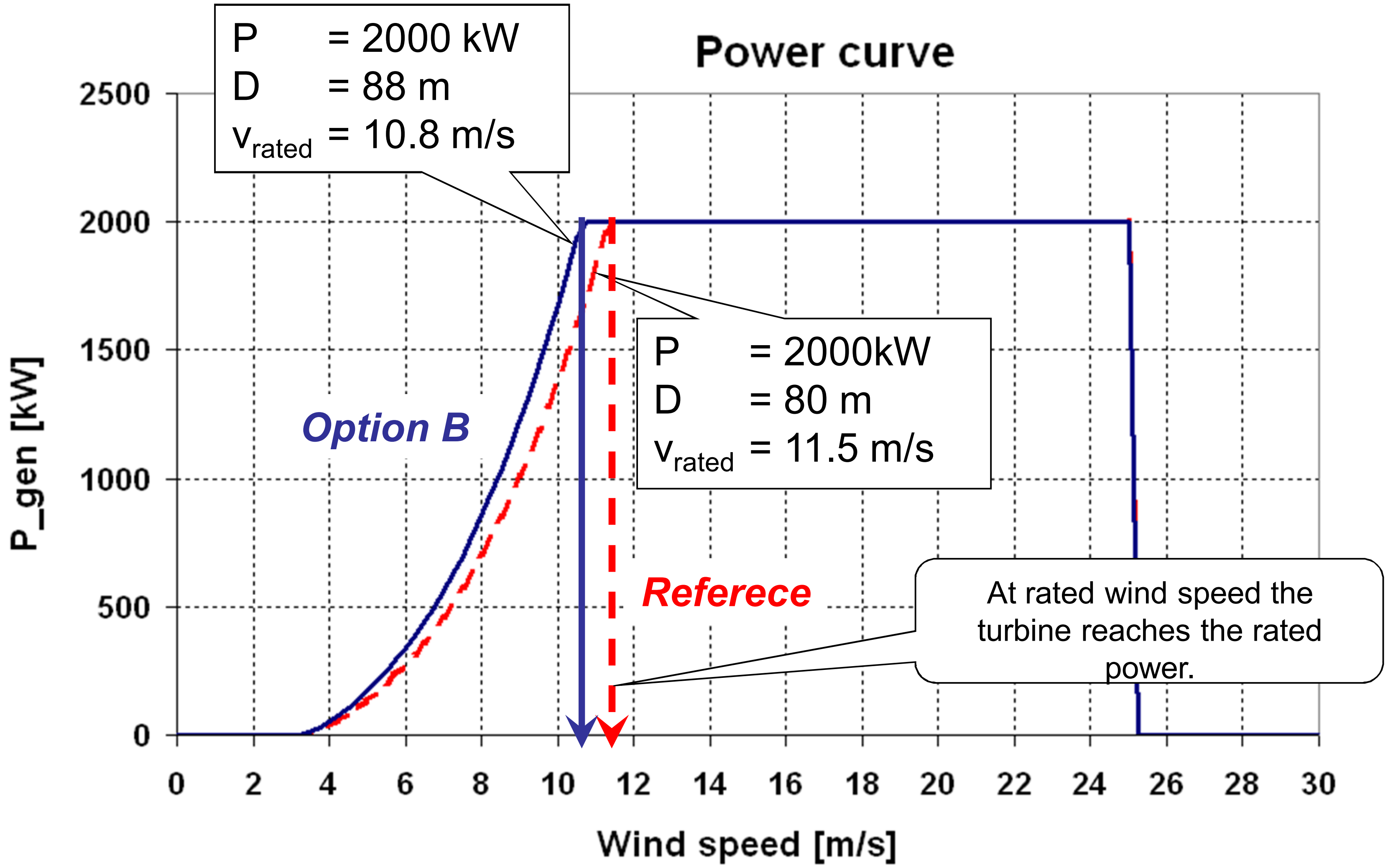
Option A: different annual wind distribution



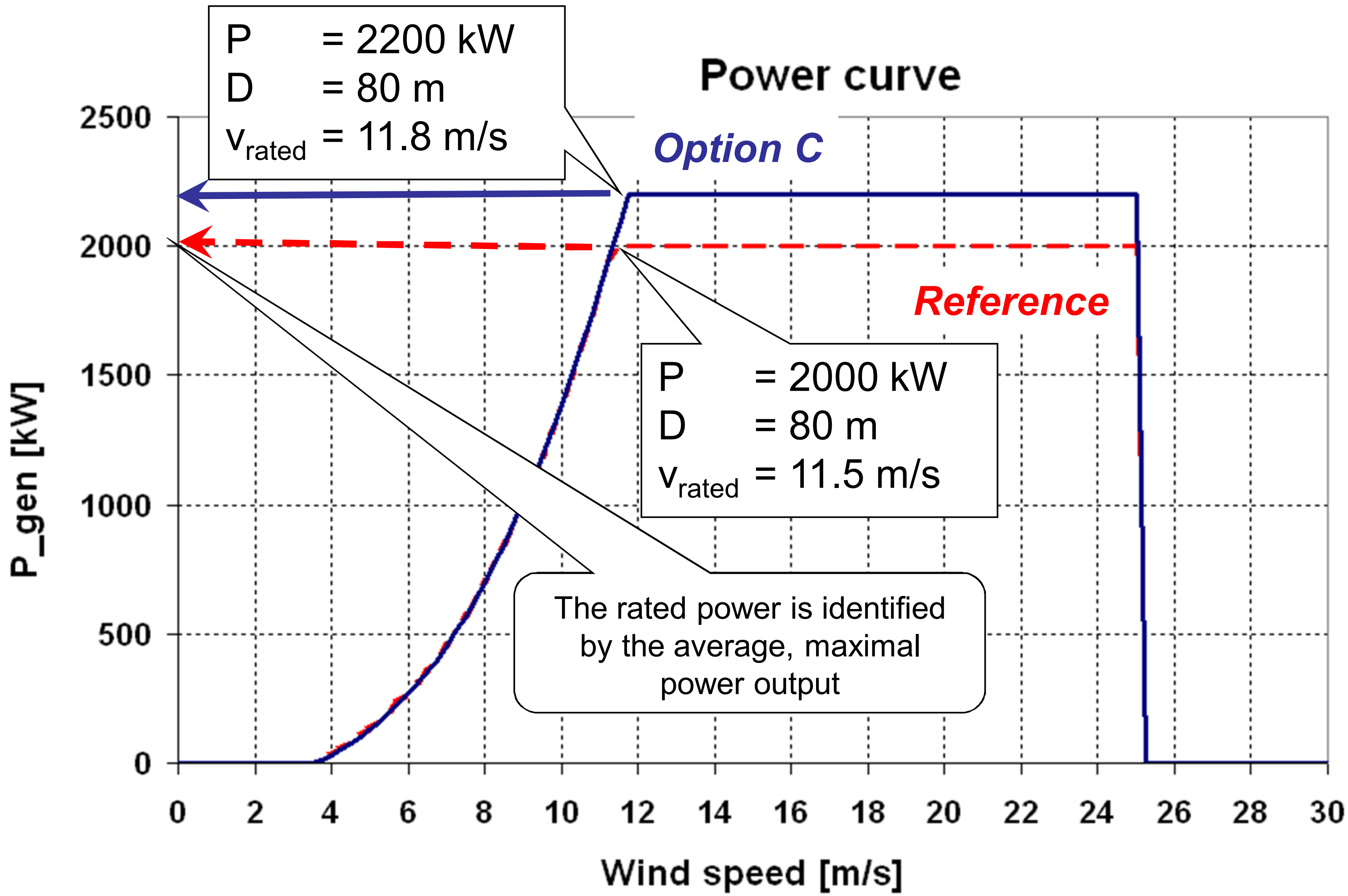
Option A: different annual wind distribution



Option B: different wind turbines – larger rotor



Option C: different wind turbines – rated power



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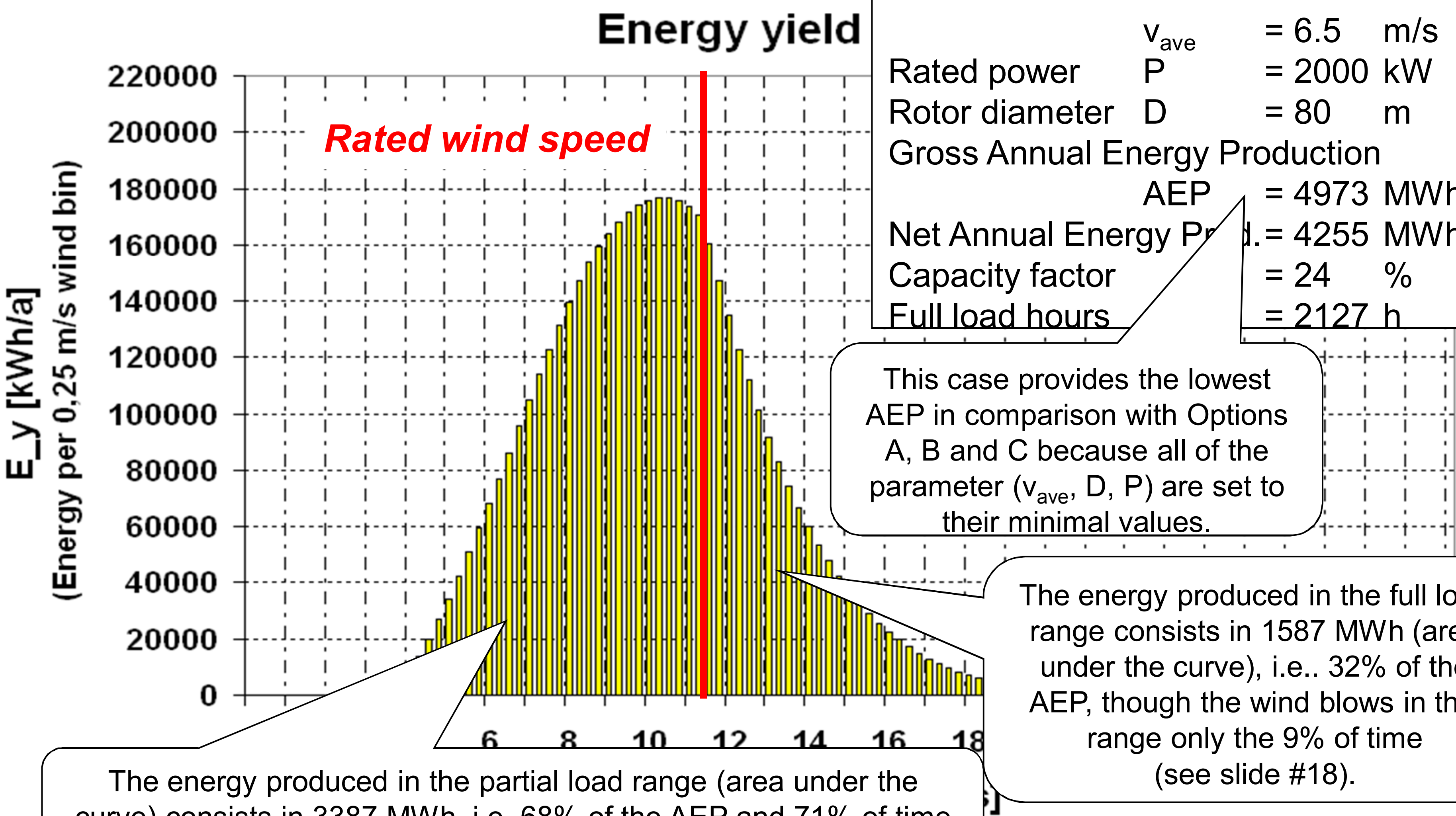
Reference case



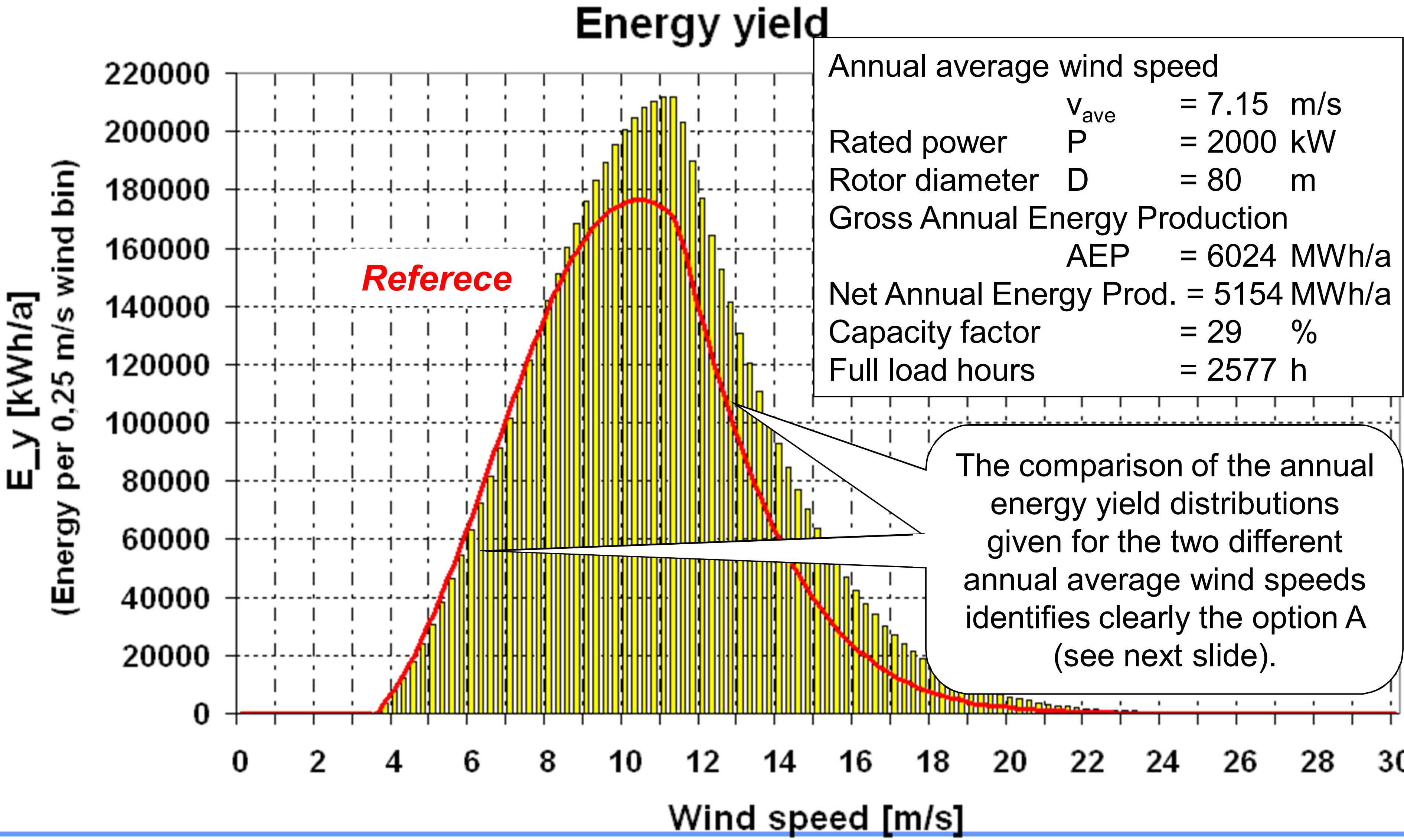
Annual average wind speed v_{ave} = 6.5 m/s
Rated power P = 2000 kW
Rotor diameter D = 80 m
Gross Annual Energy Production AEP = 4973 MWh/a
Net Annual Energy Prod. = 4255 MWh/a
Capacity factor = 24 %
Full load hours = 2127 h

This case provides the lowest AEP in comparison with Options A, B and C because all of the parameter (v_{ave}, D, P) are set to their minimal values.

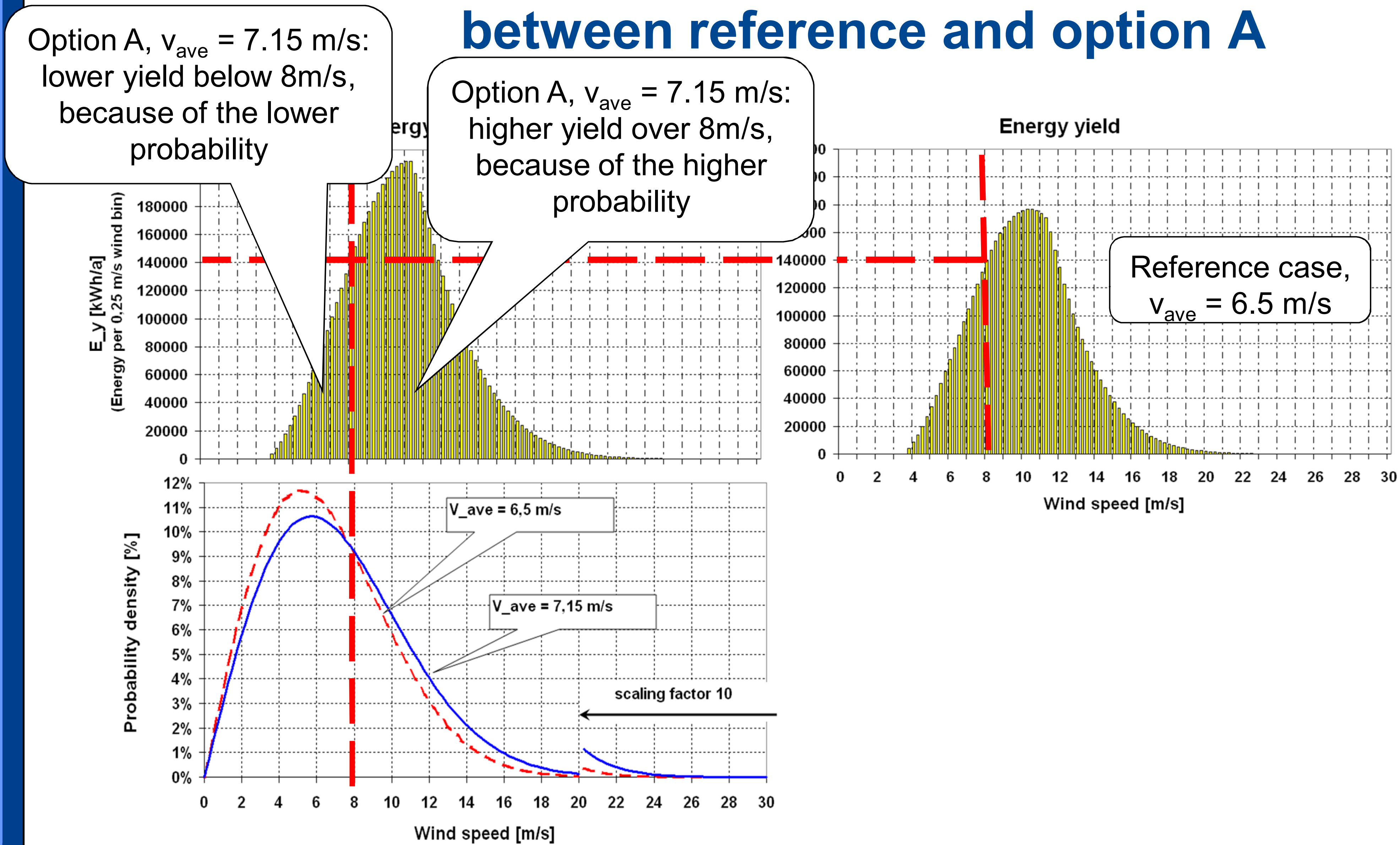
The energy produced in the full load range consists in 1587 MWh (area under the curve), i.e.. 32% of the AEP, though the wind blows in this range only the 9% of time (see slide #18).

The energy produced in the partial load range (area under the curve) consists in 3387 MWh, i.e. 68% of the AEP and 71% of time (see slide #18).

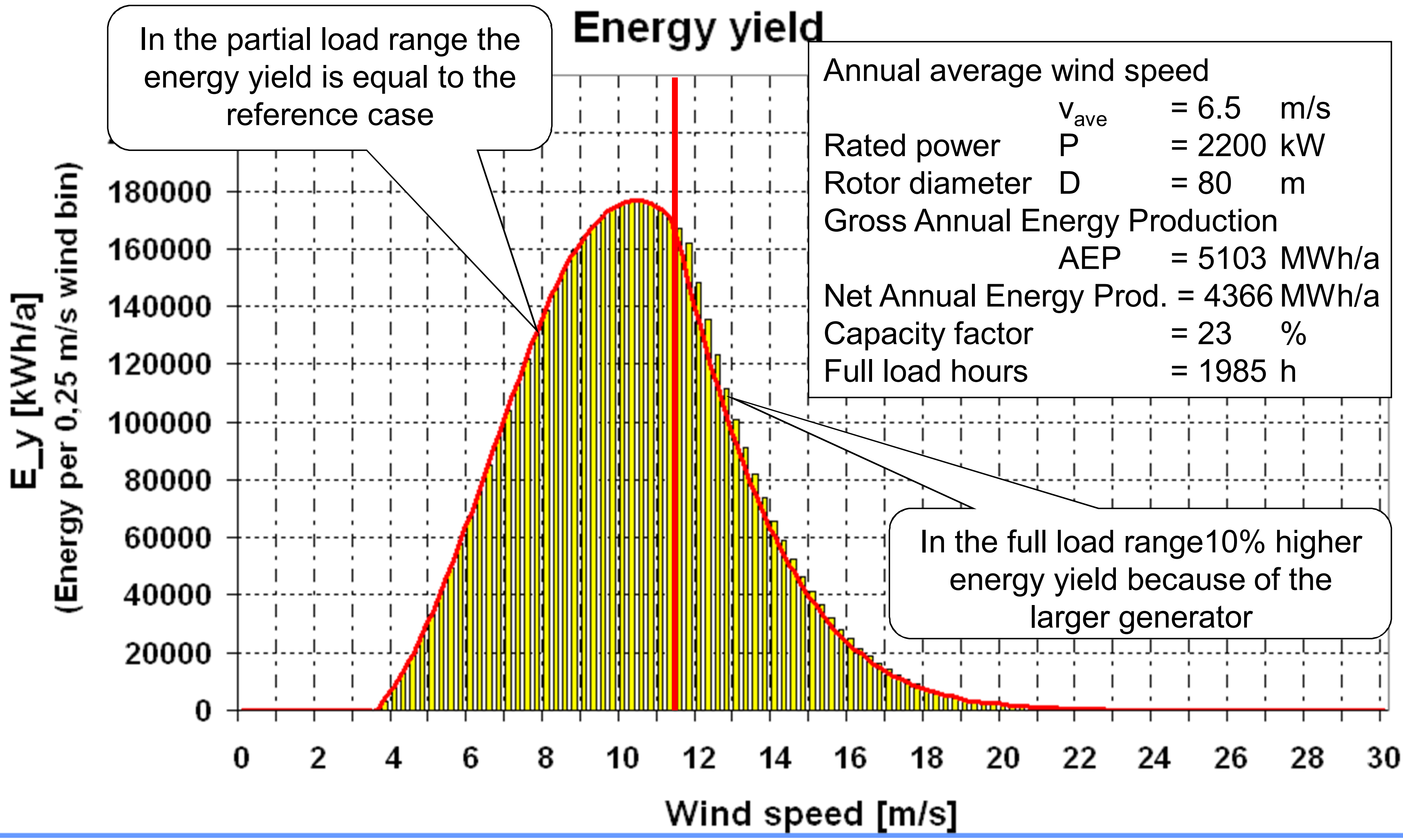
Different annual wind distribution – option A (stronger wind)



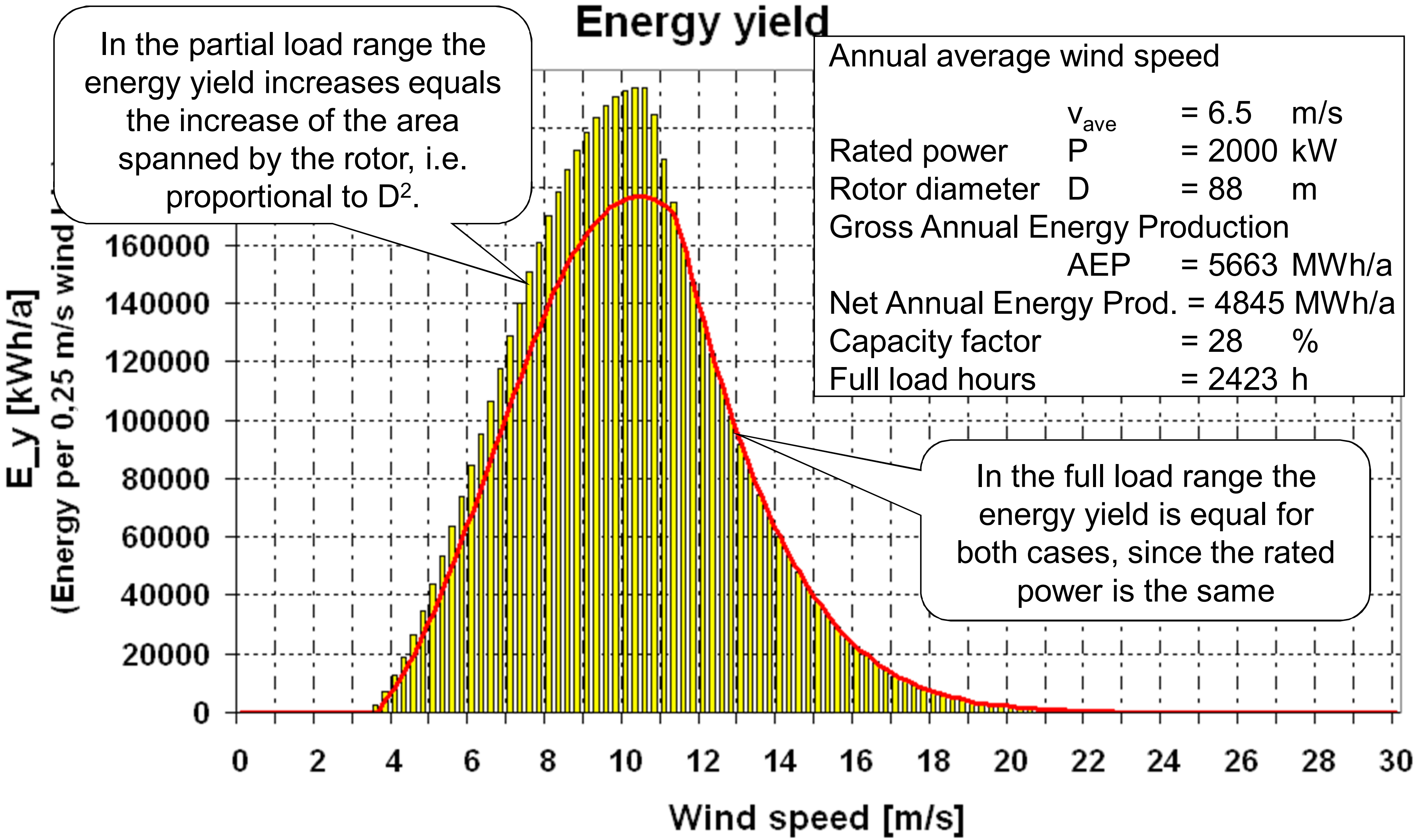
Different annual wind distribution – comparison between reference and option A



Different wind turbine – option C (rated power)



Different wind turbine – option B (rotor diameter)



Comparison of the option

	Reference Case	Option A	Option B	Option C
Annual average wind velocity, v_{ave}	6.5 m/s	7.15 m/s	6.5 m/s	6.5 m/s
Rated power, P	2000 kW	2000 kW	2000 kW	2200 kW
Rotor diameter, D	80 m	80 m	88 m (Ø + 10%, area + 21%)	80 m
Specific rating	398 W/m2	398 W/m2	329 W/m2	438 W/m2
Gross Annual Energy Production, AEP	4973 MWh	6024 MWh	5663 MWh	5103 MWh
Relative AEP	100 %	121 %	114%	103%

Summary

- In the case of a site characterized by relative weak wind with v_{ave} = 6.5 m/s the best choice to increase the AEP is to set the nacelle on a higher tower, or, if it is not possible it may be considered to search for a windier site. A 10% stronger annual average wind provide 21% more energy yield. A larger rotor diameter brings little lower increase in the energy production (14%). The example of a higher rated power at the reference site, with the reference rotor diameter provides too low increase in the AEP to bring economical advantages.
- In site with strong annual wind (v_{ave} = 8 to 10 m/s) opposite conclusion may be state. In such sites the frequency of full load wind conditions is significantly higher and therefore the increase of the rated power may be effective and economically convenient. On the other hand, there larger rotors would cause higher mechanical loads and would require expensive reinforcement of the blades and of the structure.

⇒ Weak wind site: large rotors and high towers combined with low rated power, i.e. a low specific rating (ratio between rated power and rotor area [kW/m²])

⇒ Strong wind site: relatively small rotors combined with relatively short towers as well as large rated power, i.e. a high specific rating.