Universitat Politècnica de Catalunya

Renewable Energy Systems

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UNITE! Programme

SECOND EVALUATIVE ACTIVITY

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EXERCISE 1 – WIND ENERGY SYSTEMS

The aim of this first exercise is to evaluate the electrical energy production of three different wind turbines located east of the city of Geneva.

POINT 1

a. In the first point it is required to choose the specific location of the turbine, following some guidelines:

- The location has to be east of the city of Geneva
- It has to be an area with high wind potential
- It does not have to be in a region of federal government interests

The chosen point is therefore near “La Tour”, as shown in the figures below. The high intensity blue in the figures represents a region with high wind potential:

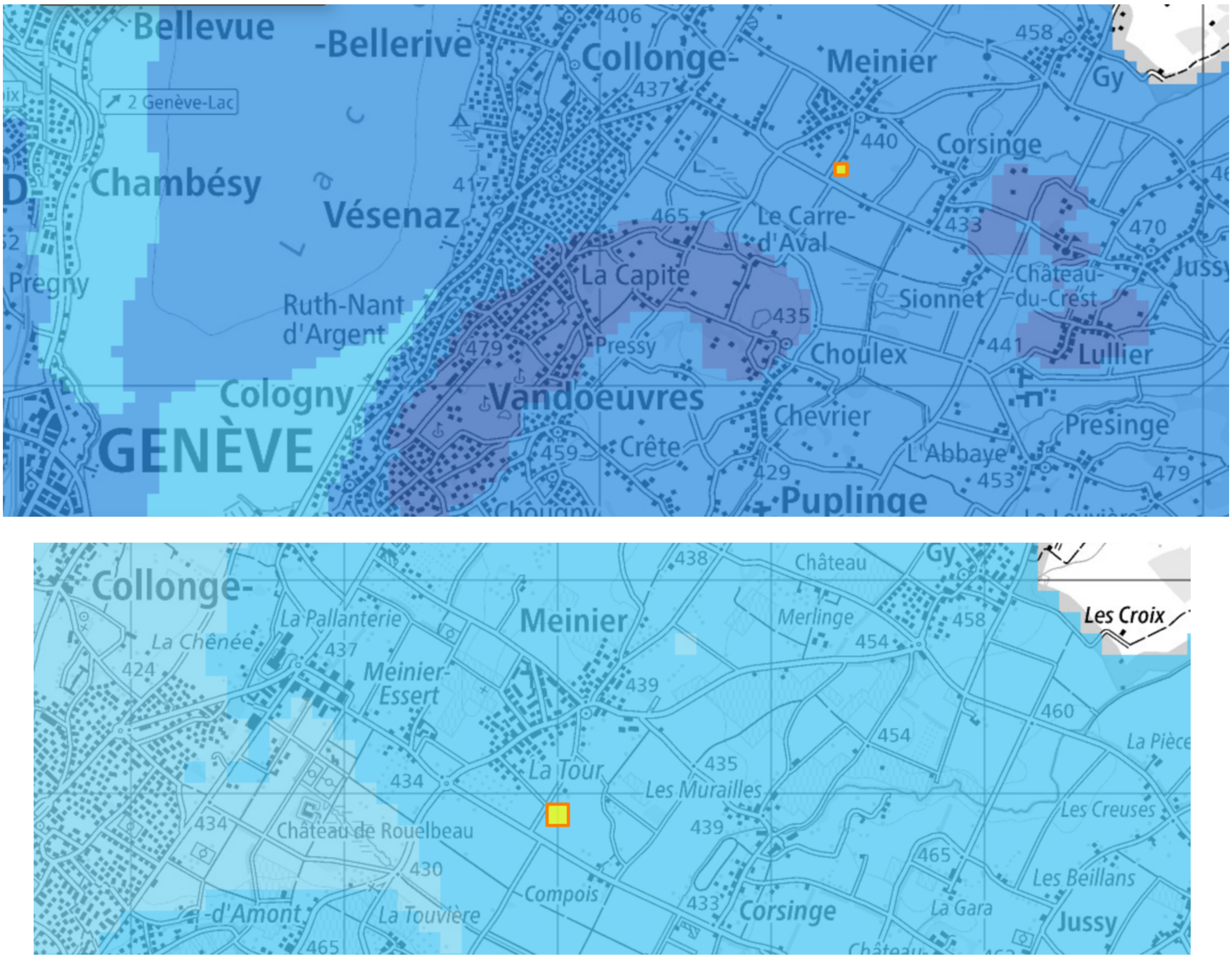

Figure 1, 2 – Chosen Location

The location is not in a region of government interest, neither in a urban center, as shown in figure 3, 4:

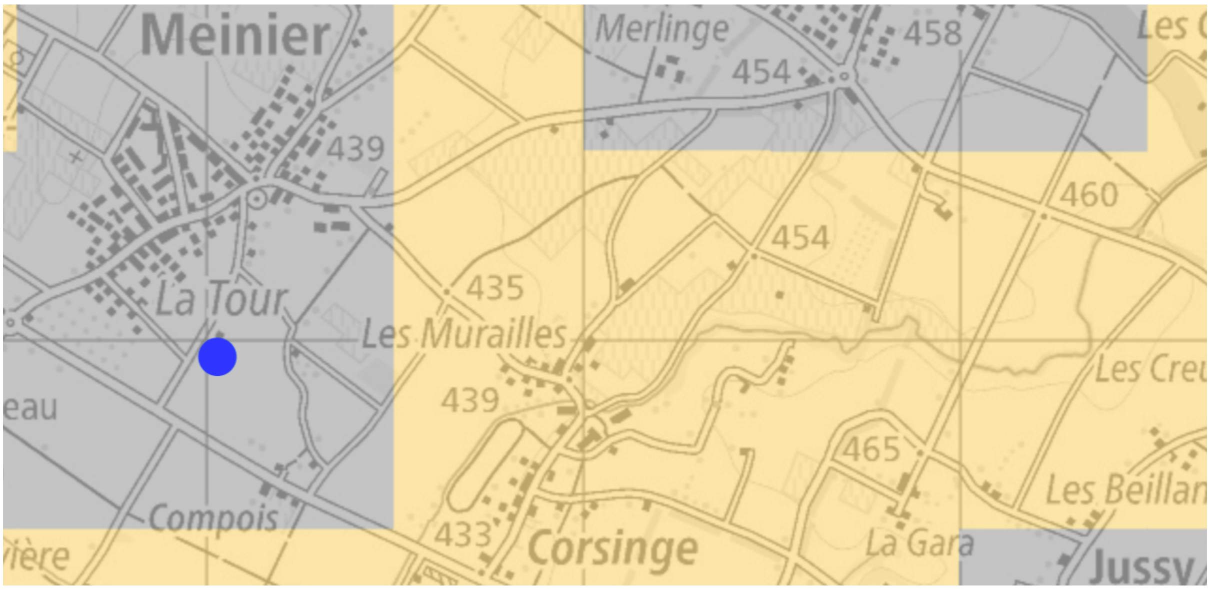

Figure 3 – Region of Government Interest (in yellow)


Figure 4 – Satellite View

b. Once the location is selected, thanks to online databases, it is possible to determine the wind rose with the wind speed direction distribution. In particular, since we are analyzing three different wind turbines with different hub heights, all the data are displayed separately for each turbine:

1. Turbine AELOS-H100 with H $_{HUB}$ = 50 m

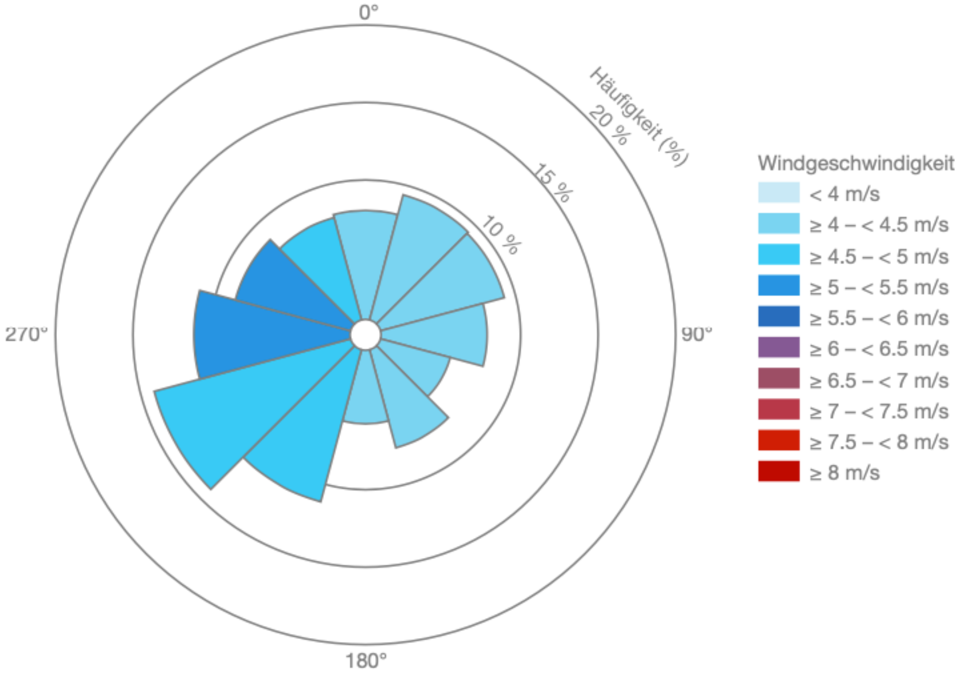

Figure 5 – Wind Rose for H $_{HUB}$ = 50 m

2. Turbine ENERCON E48/800 with H $_{HUB}$ = 75 m

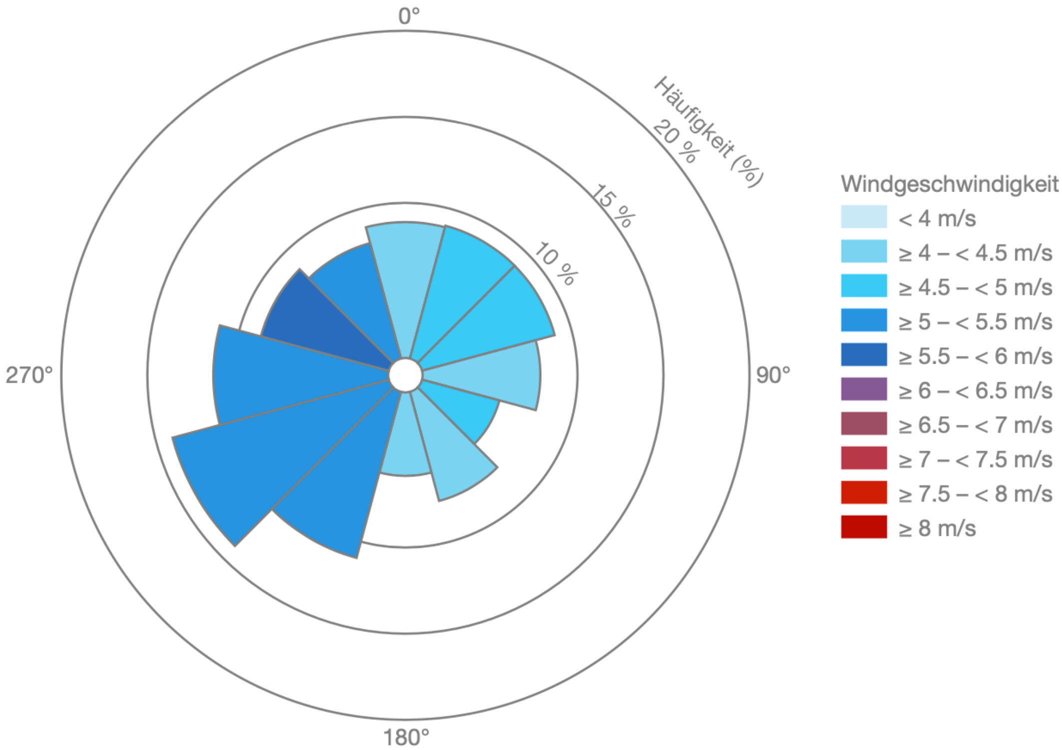

Figure 6 – Wind Rose for H $_{HUB}$ = 75 m

3. Turbine ENERCON E82/2000 with H_{HUB} = 125 m

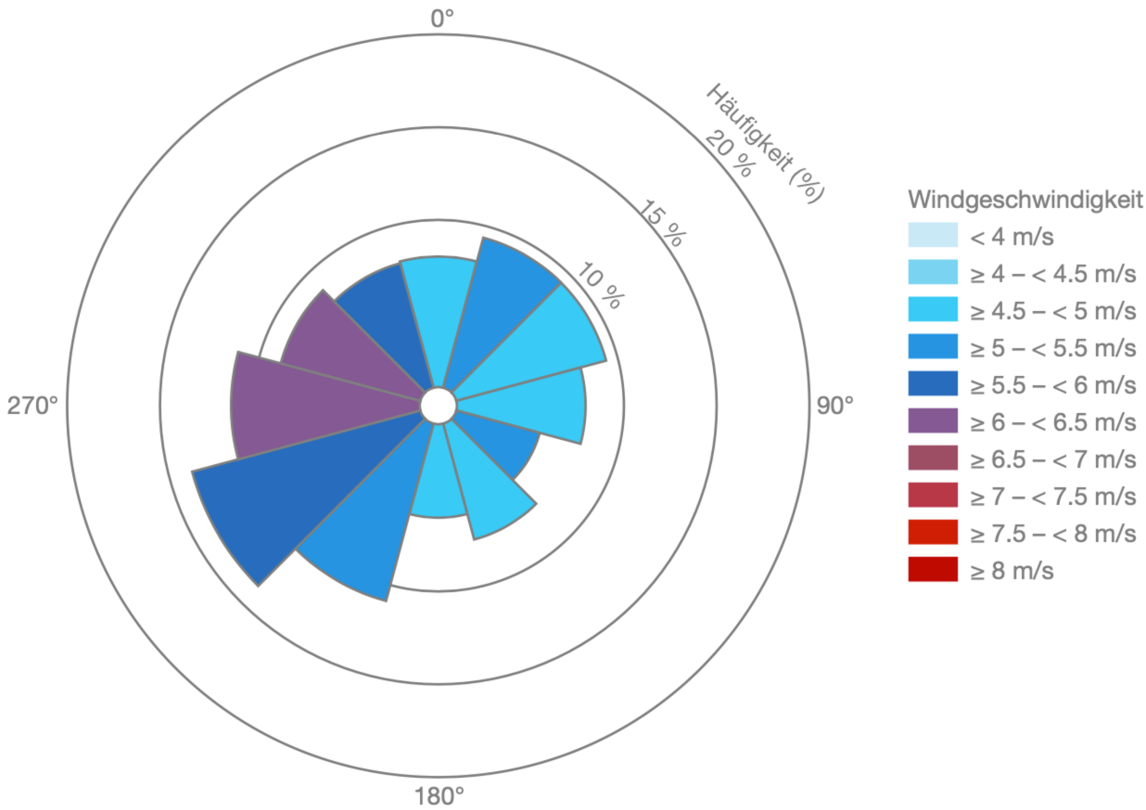

Figure 7 – Wind Rose for H_{HUB} = 125 m

As we can see, the most frequent wind direction remains constant with the increasing hub height, while the wind speed increases. This result is expected since the wind speed increases with height following a logarithmic or power law.

c. Then, also the Weibull distribution (with its parameters A and k) can be determined. As before, the results are different for the different hub heights, they are shown in the figures below:

1. Turbine AELOS-H100 with $H_{HUB} = 50$ m

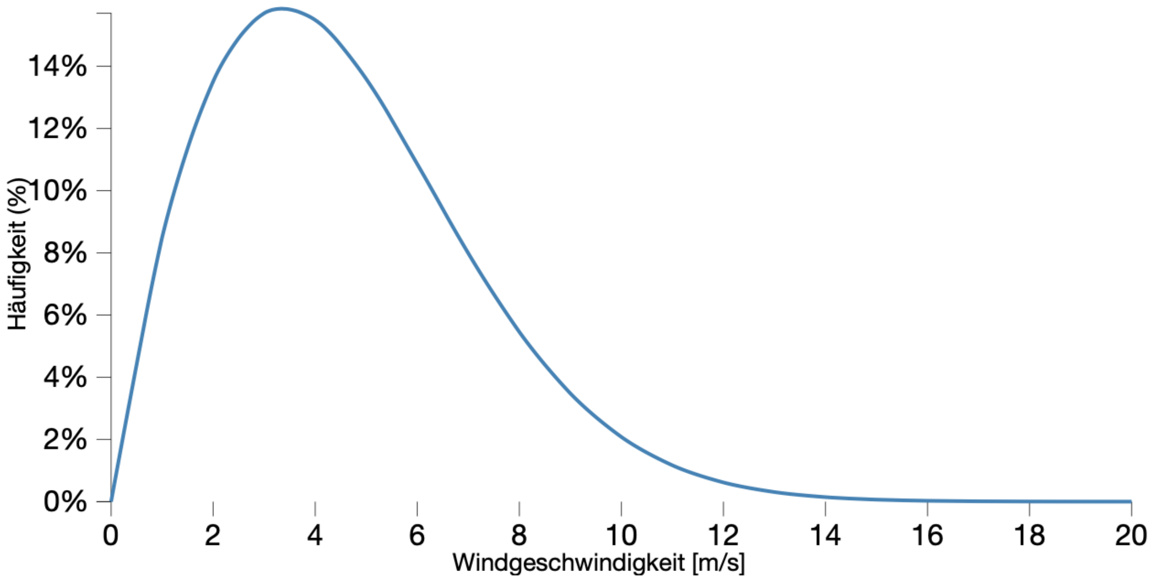

Figure 8 – Weibull Distribution for $H_{HUB} = 50$ m

Table 1 – Frequency, A and k parameters for $H_{HUB} = 50$ m

Wind direction	Frequency (%)	Average speed	A.	k
total	100%	4.6 m / s	5.2 m / s	1.9
345 ° - 15 °	7%	4.1 m / s	4.6 m / s	1.7
15 ° - 45 °	9%	4.4 m / s	5.0 m / s	1.9
45 ° - 75 °	9%	4.3 m / s	4.8 m / s	1.8
75 ° - 105 °	7%	4.0 m / s	4.5 m / s	1.7
105 ° - 135 °	5%	4.4 m / s	5.0 m / s	1.8
135 ° - 165 °	7%	4.0 m / s	4.5 m / s	1.8
165 ° - 195 °	5%	4.2 m / s	4.8 m / s	1.7
195 ° - 225 °	11%	4.7 m / s	5.3 m / s	2.0
225 ° - 255 °	14%	4.9 m / s	5.6 m / s	2.2
255 ° - 285 °	11%	5.1 m / s	5.7 m / s	2.1
285 ° - 315 °	8th %	5.1 m / s	5.7 m / s	1.8
315 ° - 345 °	7%	4.8 m / s	5.4 m / s	1.7

2. Turbine ENERCON E48/800 with H_{HUB} = 75 m

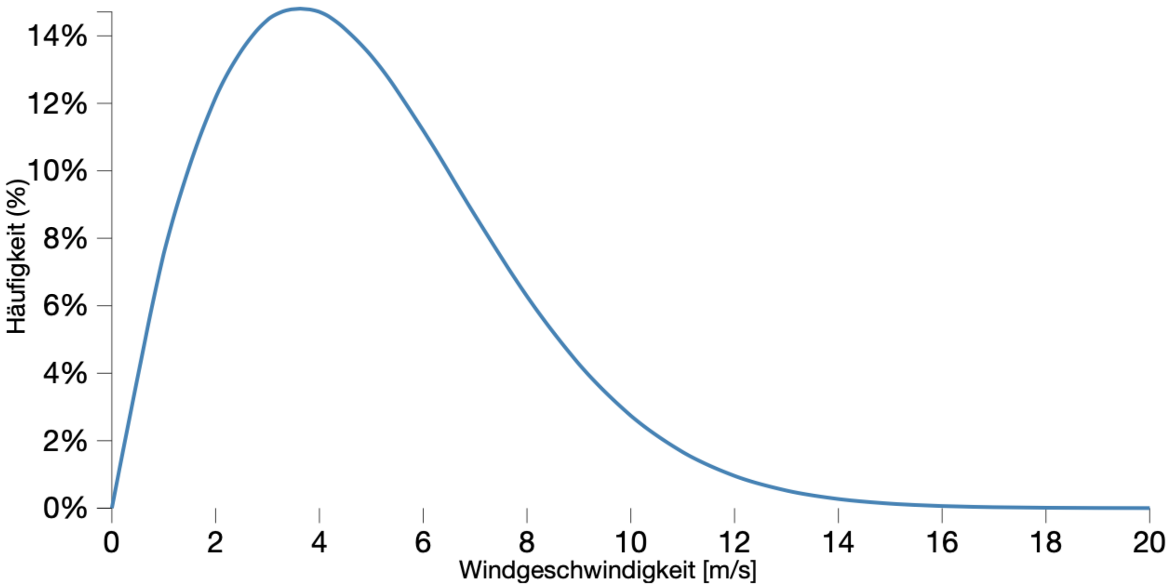

Figure 9 – Weibull Distribution for H_{HUB} = 75 m

Table 2 – Frequency, A and k parameters for H_{HUB} = 75 m

Wind direction	Frequency (%)	Average speed	A.	k
total	100%	4.9 m / s	5.5 m / s	1.9
345 ° - 15 °	8th %	4.3 m / s	4.8 m / s	1.7
15 ° - 45 °	8th %	4.9 m / s	5.5 m / s	1.9
45 ° - 75 °	8th %	4.6 m / s	5.1 m / s	1.8
75 ° - 105 °	7%	4.3 m / s	4.8 m / s	1.7
105 ° - 135 °	5%	4.7 m / s	5.3 m / s	1.7
135 ° - 165 °	7%	4.3 m / s	4.8 m / s	1.8
165 ° - 195 °	5%	4.5 m / s	5.0 m / s	1.7
195 ° - 225 °	11%	5.0 m / s	5.7 m / s	2.0
225 ° - 255 °	14%	5.3 m / s	6.0 m / s	2.2
255 ° - 285 °	11%	5.4 m / s	6.1 m / s	2.1
285 ° - 315 °	8th %	5.5 m / s	6.2 m / s	1.8
315 ° - 345 °	7%	5.2 m / s	5.9 m / s	1.8

3. Turbine ENERCON E82/2000 with H_{HUB} = 125 m

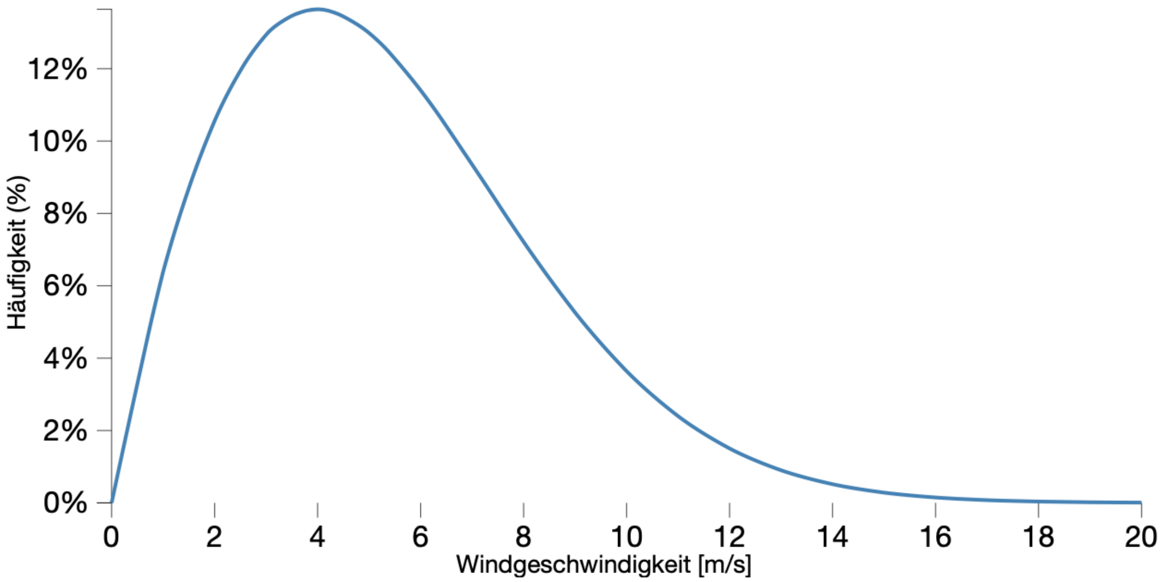

Figure 10 – Weibull Distribution for H_{HUB} = 125 m

Table 3 – Frequency, A and k parameters for H_{HUB} = 125 m

Wind direction	Frequency (%)	Average speed	A.	k
total	100%	5.3 m / s	6.0 m / s	1.9
345 ° - 15 °	7%	4.8 m / s	5.4 m / s	1.7
15 ° - 45 °	9%	5.1 m / s	5.8 m / s	1.9
45 ° - 75 °	9%	4.9 m / s	5.6 m / s	1.8
75 ° - 105 °	7%	4.6 m / s	5.2 m / s	1.7
105 ° - 135 °	5%	5.1 m / s	5.7 m / s	1.7
135 ° - 165 °	7%	4.6 m / s	5.2 m / s	1.8
165 ° - 195 °	5%	4.7 m / s	5.3 m / s	1.7
195 ° - 225 °	10%	5.4 m / s	6.2 m / s	2.0
225 ° - 255 °	13%	5.8 m / s	6.6 m / s	2.2
255 ° - 285 °	11%	6.0 m / s	6.8 m / s	2.1
285 ° - 315 °	8th %	6.1 m / s	6.8 m / s	1.9
315 ° - 345 °	7%	5.7 m / s	6.4 m / s	1.8

As already said, the average wind speed increases with the height.
To be clearer, the complete PDF file with all the results for the different heights is attached.

POINT 2

In the second point it is asked to determine the annual production of electrical energy for each of the three models.
The energy can be calculated as the power produced by the turbine for a specific wind speed, times the hours of operation at that wind speed:

$$E[kWh] = P[kW] \cdot h\ [h]$$

The power produced at a wind speed is different for each turbine and depends on its power curve, therefore it has been determined thanks to the datasheets provided by the manufacturer.
The hours of operation at a specific wind speed have been calculated thanks to the frequency of the wind speed previously obtained, with the relation:

$$h\ [h] = \frac{frequency\ [\%] \cdot 8760[h]}{100}$$

So, for the three turbines the results are:

1. Turbine AELOS-H100 with H_{HUB} = 50 m

From the datasheet of this turbine (which is attached) we know that the cut-in wind speed is 2.5 m/s, so for wind speeds below this one the turbine will not produce power, while the rated wind speed is 11 m/s, so at this speed we will reach the rated power equal to 100 kW. In particular, the power curve for this turbine is:

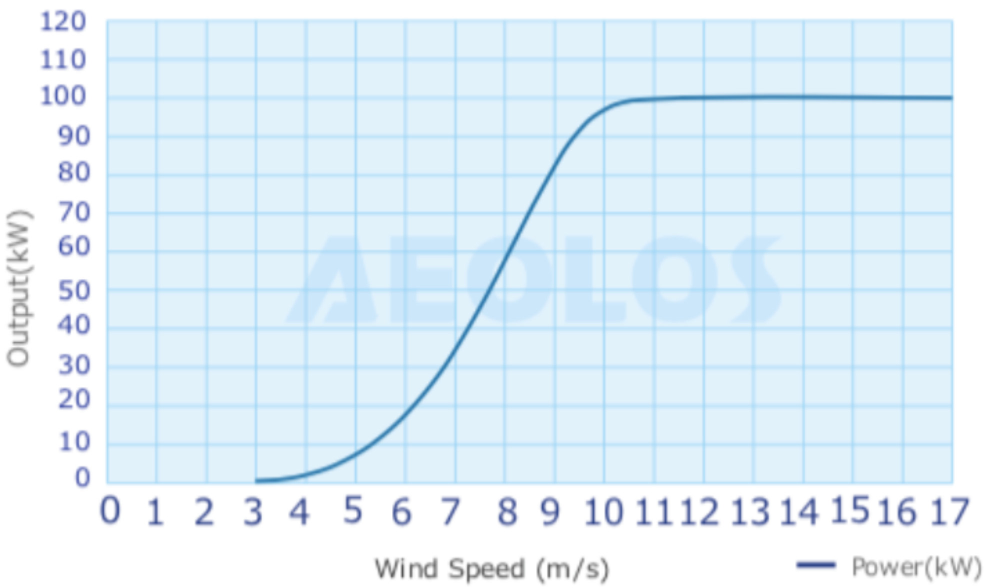

Figure 11 – Power Curve for AELOS-H100

To be clearer, the numerical value of the power with respect to the wind speed are displayed in the table below:

Table 4 - Power Values for AELOS-H100

Wind Speed(m/s)	Power Coefficient	Power Output(kW)	Annual Energy Yield(MWh)
3.0	0.13	0.92	38.94
4.0	0.21	3.47	100.01
5.0	0.39	12.23	183.80
6.0	0.40	21.75	272.90
7.0	0.40	34.54	359.87
8.0	0.40	51.57	434.22
9.0	0.40	73.42	498.58
10.0	0.37	94.05	548.31
11.0	0.33	100.00	583.33
12.0	0.29	100.00	605.65

Once the power curve is known, it is possible to compute the energy produced with the formulas shown before. The results are:

Table 5 – Energy Produced by AELOS-H100

Wind Speed [m/s]	Frequency [%]	Hours [h]	Power [kW]	Energy [kWh]
0	0	0	0	0
1	8,5	744,6	0	0
2	13,5	1182,6	0	0
3	15,7	1375,32	0,92	1265,2944
4	15,5	1357,8	3,47	4711,566
5	13,6	1191,36	12,23	14570,3328
6	10,9	954,84	21,75	20767,77
7	8	700,8	34,54	24205,632
8	5,5	481,8	51,57	24846,426
9	3,5	306,6	73,42	22510,572
10	2,1	183,96	94,05	17301,438
11	1,2	105,12	100	10512
12	0,6	52,56	100	5256
13	0,3	26,28	100	2628
14	0,1	8,76	100	876
15	0,1	8,76	100	876
16	0	0	100	0
17	0	0	100	0
TOTAL	99,1	8681,16	991,95	150327,0312

The analysis of this turbine stops for a wind speed of 15 m/s because, even if this value is below the cut-off velocity, the wind never blows at higher speeds in this location for this hub height.

2. Turbine ENERCON E48/800 with H $_{HUB}$ = 75 m

The power data for this turbine have been found on the website: https://www.thewindpower.net/turbine_en_3_enercon_e48-800.php, from this data we know that the cut-in velocity is 3 m/s, the rated is 14 m/s and the cut-off is 25 m/s.
The power curve for this turbine is:

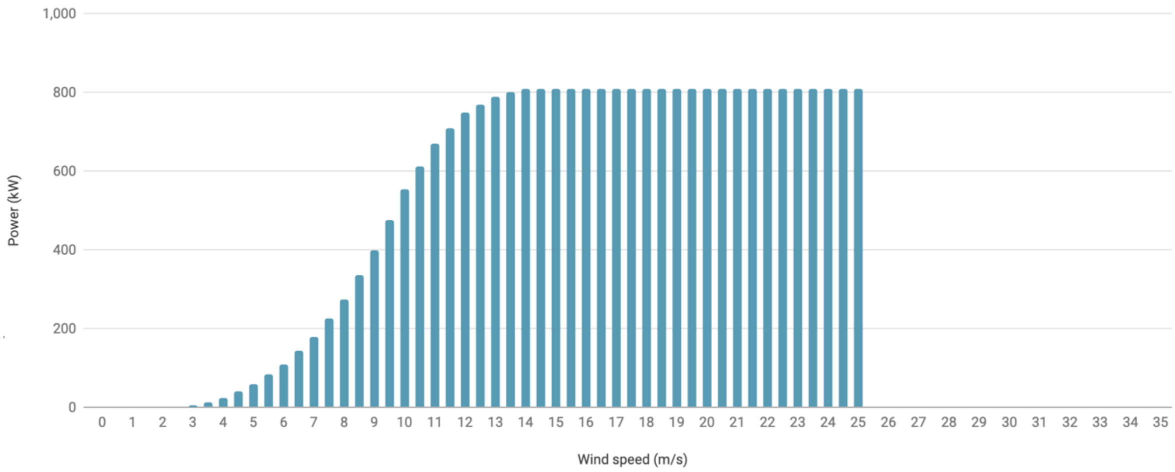

Figure 12 – Power Curve for ENERCON E48/800

The obtained energy production is:

Table 6 – Energy Produced by ENERCON E48/800

Wind Speed [m/s]	Frequency [%]	Hours [h]	Power [kW]	Energy [kWh]
0	0	0	0	0
1	7,5	657	0	0
2	12,2	1068,72	0	0
3	14,5	1270,2	5	6351
4	14,7	1287,72	25	32193
5	13,4	1173,84	60	70430,4
6	11,2	981,12	110	107923,2
7	8,7	762,12	180	137181,6
8	6,3	551,88	275	151767
9	4,3	376,68	400	150672
10	2,7	236,52	555	131268,6
11	1,7	148,92	671	99925,32
12	1	87,6	750	65700
13	0,5	43,8	790	34602
14	0,3	26,28	800	21024
15	0,1	8,76	800	7008
16	0,1	8,76	800	7008
17	0	0	800	0
TOTAL	99,2	8689,92	7021	1023054,12

In this case the analysis is stopped for 16 m/s, even if the cut-off speed is 25 m/s, for this location and this height the wind does not blow at higher speeds.

3. Turbine ENERCON E82/2000 with H_{HUB} = 125 m

The data for this turbine have been found on the website: https://www.thewindpower.net/turbine_en_6_enercon_e82-2000.php, in this case the cut-in speed is lower, equal to 2 m/s, the rated speed is 12.5 m/s, while the cut-off speed is equal to the previous one.

The power curve is shown in the following figure:

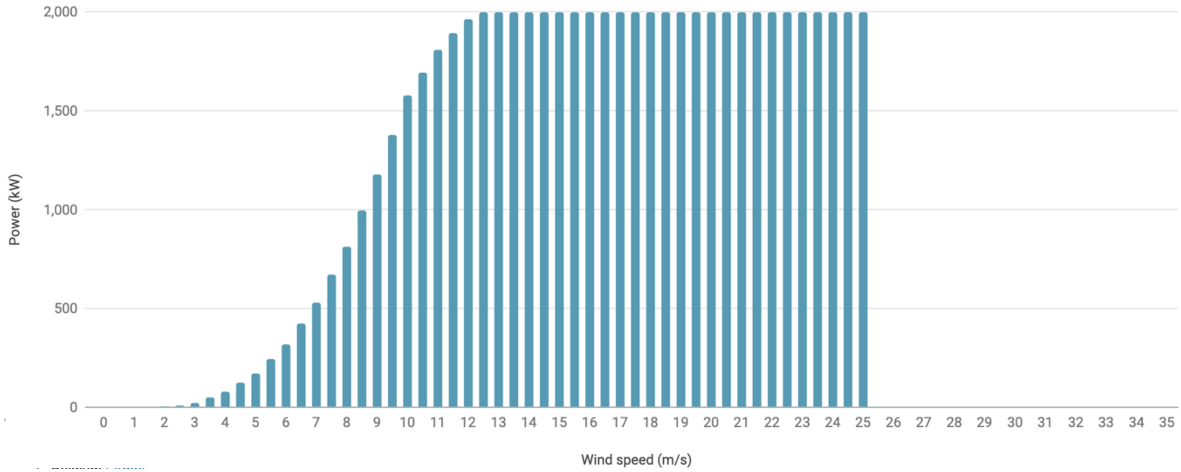

Figure 13 – Power Curve for ENERCON E82/2000

The obtained results are:

Table 7 – Energy Produced by ENERCON E48/800

Wind Speed [m/s]	Frequency [%]	Hours [h]	Power [kW]	Energy [kWh]
0	0	0	0	0
1	6,4	560,64	0	0
2	10,6	928,56	3	2785,68
3	12,9	1130,04	25	28251
4	13,6	1191,36	82	97691,52
5	13	1138,8	174	198151,2
6	11,4	998,64	321	320563,44
7	9,4	823,44	532	438070,08
8	7,2	630,72	815	514036,8
9	5,3	464,28	1180	547850,4
10	3,6	315,36	1580	498268,8
11	2,4	210,24	1810	380534,4
12	1,5	131,4	1965	258201
13	0,9	78,84	2000	157680
14	0,5	43,8	2000	87600
15	0,3	26,28	2000	52560
16	0,1	8,76	2000	17520
17	0,1	8,76	2000	17520
TOTAL	99,2	8689,92	18487	3617284,32

As expected, the turbine that produces more energy is the third one. In fact, it has a higher hub height so the wind blows faster and allows the turbine to produce more electrical energy. Also, the rotor has a bigger radius that allows this turbine to catch more wind.

POINT 3

In this point it is asked to take in consideration the first turbine in order to make a comparison between the value of annual energy produced that is provided by the manufacturer and the value found thanks to our calculations.

Since the average wind speed for this hub height is 4.6 m/s and the manufacturer provides the energy value for 4 m/s and 5 m/s (Table 4), an interpolation has been done and the annual average wind speed found is equal to 150.284 MW.
The interpolation is a linear one and int formulation is:

$$\frac{4.6-4}{5-4}=\frac{P(v_{avg})-P(4)}{P(5)-P(4)}$$

The datasheet value matches the one previously calculated, equal to 150.327 MW, so it is possible to state that the calculations are accurate.

The result is also summarized in the table below:

Table 8 – Energy Provided by the Manufacturer

V average	4,6	m/s
Energy Datasheet	150,284	MWh

POINT 4

In this point it is asked to determine the cost for each kWh generated by the three turbines, so the project cost has been divided by the total energy produced in a year, also divided by the years of operation of the plant. In this case the lifespan of the plant has been considered equal to 20 years for the three turbines.

$$c\ [Euro/kWh]=\frac{Project\ Cost\ [Euro]}{Energy\ \left[\frac{kWh}{y}\right]\cdot Lifespan\ [y]}$$

The results are:

Table 9 – Cost per kWh

	Cost [Euro]	Energy [kWh]	Unit Cost [Euro/kWh]
Turbine 1	400000	150327,0312	0,133043271
Turbine 2	1200000	1023054,12	0,058647924
Turbine 3	2600000	3617284,32	0,035938563
Lifespan	20	years	

POINT 5

In this point it is asked to determine the average distance between the turbines in order to minimize the wake effect.

The chosen turbine, the one with the lower cost for unit energy produced, is the third one. Analyzing the wind rose for this turbine, it is possible to see that the most frequent wind direction is South-West, therefore the predominant wind direction will be the one parallel to the side of length 2 km, while the perpendicular wind direction will be the one parallel to the side of length 1.3 km.

For the dominant wind direction, the recommended distance is from 7 to 10 times the rotor diameter, while for the perpendicular we have from 3 to 5 times the rotor diameter. Multiplying the rotor diameter times these factors (7 and 10 for the predominant direction and 3 and 5 for the perpendicular direction) we obtain:

Table 10 – Distances Between Turbines

	Max	Min	Avg
D dominant [m]	820	574	697
D perpendicular [m]	410	246	328

Dividing the length of the side with the average distance between turbines, it is possible to find out the number of turbines per side:

Table 11 – Number of Turbines per Side

	Actual	Rounded
N dominant [-]	2,869440459	3
N perpendicular [-]	3,963414634	4
Total N of Turibes	12	-

So, on the dominant direction there will be 3 turbines, while for the perpendicular there will be 4 turbines, for a total for 12 turbines.

EXERCISE 2 – HYBRID PHOTOVOLTAIC THERMAL COLLECTORS

The aim of this exercise is to find out whether is convenient to install a hybrid PV/T plant or to install separately PV panels and thermal collectors.

The data provided are summarized in the table below:

Collector	P [W/m2]	C [Euro/W]
PV/T	591	0,8
PV	190	1,5
T	856	0,7
A tot	100	m2

POINT 1

In this point it is asked to determine if the PV/T hybrid configuration can produce more power than the separate configuration.

To answer this question, the power that the PV/T configuration can produce has been calculated as:

$$P\ [W] = P\ \left[\frac{W}{m2}\right] \cdot A\ tot\ [m2]$$

The obtained result is P = 59100 W.

Regarding the configuration in which the PV and thermal collectors are separated, since there is not a fixed area combination, their power produced has been analyzed for several combinations from 0 m^2 to 100 m^2 with a step of 5 m^2.

The results are summarized in the table below:

Table 1 – Power for Separate PV and Thermal Configuration

A PV [m2]	A T [m2]	P PV [W]	P T [W]	P TOT [W]
0	100	0	85600	85600
5	95	950	81320	82270
10	90	1900	77040	78940
15	85	2850	72760	75610
20	80	3800	68480	72280
25	75	4750	64200	68950
30	70	5700	59920	65620
35	65	6650	55640	62290
40	60	7600	51360	58960
45	55	8550	47080	55630
50	50	9500	42800	52300
55	45	10450	38520	48970
60	40	11400	34240	45640
65	35	12350	29960	42310
70	30	13300	25680	38980
75	25	14250	21400	35650
80	20	15200	17120	32320
85	15	16150	12840	28990
90	10	17100	8560	25660
95	5	18050	4280	22330
100	0	19000	0	19000

With these results it is possible to say that the power produced by the hybrid PV/T system can be higher with respect to the one produced by the separate configuration for an area of PV panels that is equal to 40 m^2 or higher (as a consequence, the thermal collector area has to be 60 m^2 or lower).

POINT 2

In this point it is asked if the cost of installing a hybrid PV/T system can be lower with respect to the separate configuration.

The cost of the installation is calculated as:

$$C\ [Euro] = C\left[\frac{Euro}{W}\right] \cdot P\ [W]$$

For the hybrid configuration it is equal to 47280 Euro, it has been obtained thanks to the power calculated in the previous point.

For the separate configuration the same analysis of the first point has been performed, the results are summarized below:

Table 2 – Cost for Separate PV and Thermal Configuration

A PV [m2]	A T [m2]	P PV [W]	P T [W]	P TOT [W]	C PV [Euro]	C T [Euro]	C TOT [Euro]
0	100	0	85600	85600	0	59920	59920
5	95	950	81320	82270	1425	56924	58349
10	90	1900	77040	78940	2850	53928	56778
15	85	2850	72760	75610	4275	50932	55207
20	80	3800	68480	72280	5700	47936	53636
25	75	4750	64200	68950	7125	44940	52065
30	70	5700	59920	65620	8550	41944	50494
35	65	6650	55640	62290	9975	38948	48923
40	60	7600	51360	58960	11400	35952	47352
45	55	8550	47080	55630	12825	32956	45781
50	50	9500	42800	52300	14250	29960	44210
55	45	10450	38520	48970	15675	26964	42639
60	40	11400	34240	45640	17100	23968	41068
65	35	12350	29960	42310	18525	20972	39497
70	30	13300	25680	38980	19950	17976	37926
75	25	14250	21400	35650	21375	14980	36355
80	20	15200	17120	32320	22800	11984	34784
85	15	16150	12840	28990	24225	8988	33213
90	10	17100	8560	25660	25650	5992	31642
95	5	18050	4280	22330	27075	2996	30071
100	0	19000	0	19000	28500	0	28500

It is possible to state that the hybrid configuration is cheaper for a PV panels area that is lower or equal than 40 m^2 (and a thermal collector area that is higher or equal than 60 m^2).

POINT 3

In conclusion we can say that the PV/T hybrid configuration is feasible if the PV panels and the thermal collector in the separate configuration have areas respectively of 40 m^2 and 60 m^2. In this case the PV/T hybrid configuration produces more power and has less cost with respect to the separate configuration.

On the contrary, for lower PV areas, the separate configuration produces more power than the hybrid, while for higher PV areas the cost of the collectors is lower in the separate configuration.