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Session 2b: Wind power spatial planning techniques

IRENA Global Atlas
Spatial planning techniques
2-day seminar

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Central questions we want to answer

- After having identified those areas which are potentially available for renewables, we want to estimate…
  - what the potential solar **wind capacity** per km² and in total is (W/km²), and,
  - **how much electricity** (Wh/km²/a) can be generated in areas with different wind regimes.
- We also need to know which parameters are the **most sensitive** ones in order to identify the most important input parameters.

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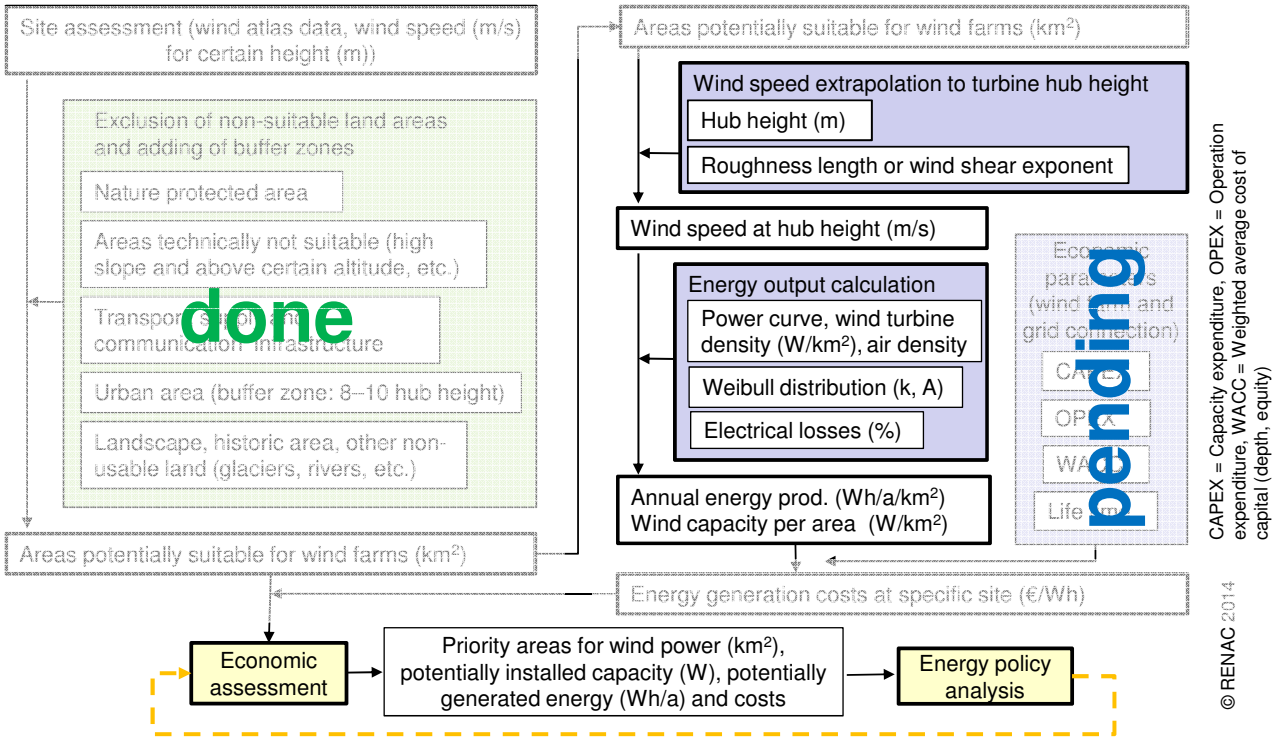

CAPEX = Capacity expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (depth, equity)

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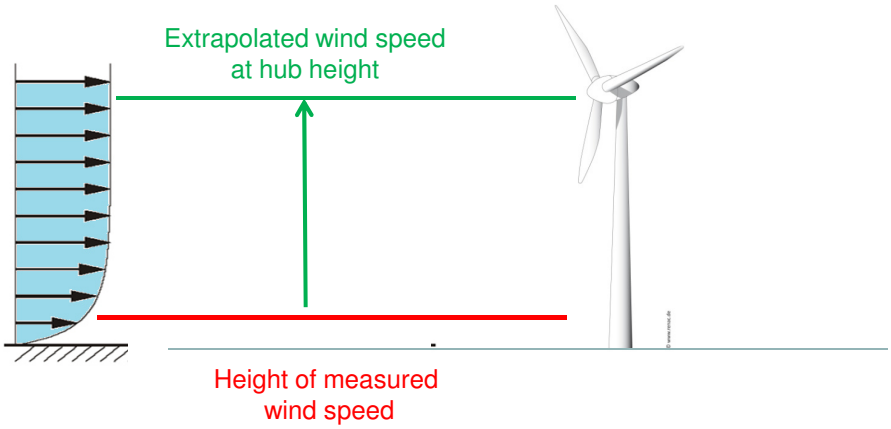
Agenda

1. Overview on wind energy estimation
2. Formation of wind
3. Technical aspects we need to know
4. Spatial setup of wind farms
5. Estimating wind electricity yield
6. Worked example: Estimating wind capacity and yield at a given site

1. OVERVIEW ON WIND ENERGY ESTIMATION

Wind speed extrapolation



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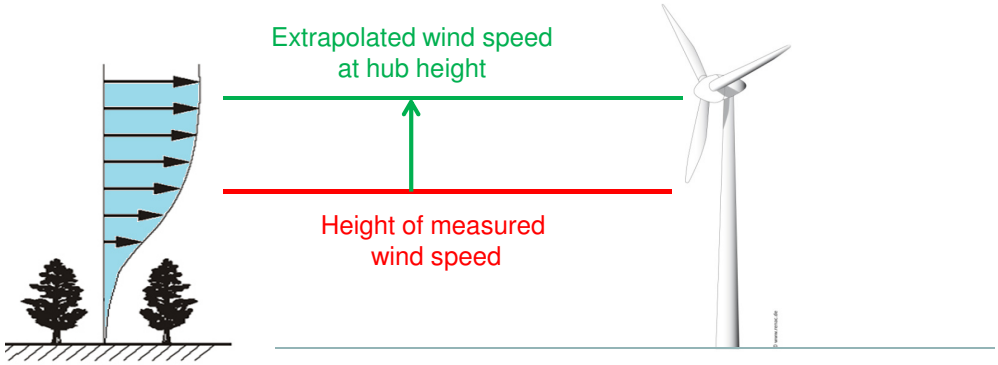
Wind speed extrapolation also depends on surroundings



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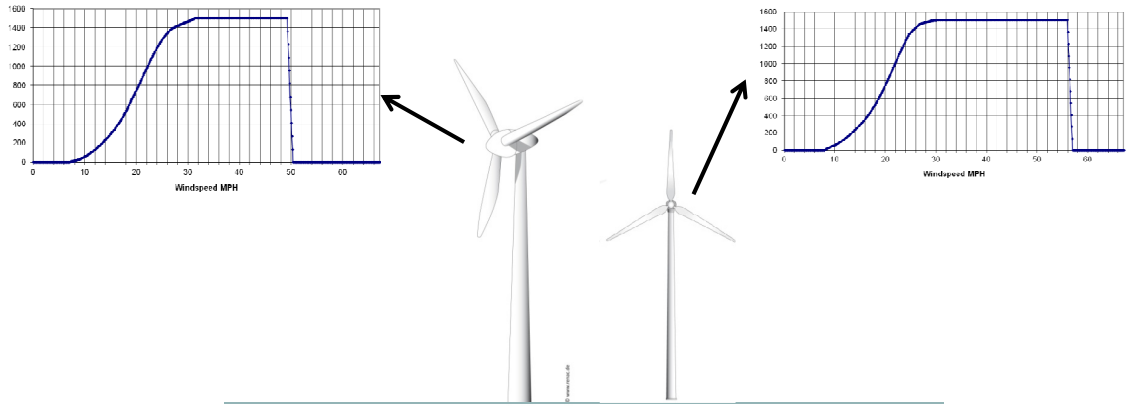
Each turbine type has its characteristic power curve



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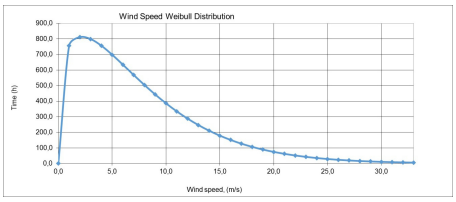
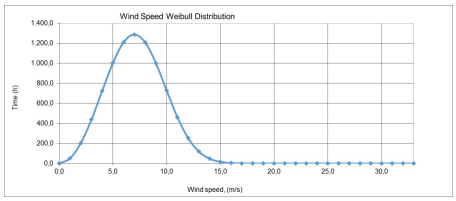
At each site, wind has its own timely distribution

Site A



Site B



Average wind speed data is not sufficient, wind speed distribution is crucial!

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Estimating wind energy generation

- Estimation of wind energy generation depends on a **large number of factors** and should be carried out with great care.
- It is necessary to find a representative mix of **suitable** wind turbines in order to get a good estimate of the wind energy that could be produced.
- If there is, the resulting capacity factor (full-load hours) should be **cross-checked** with existing wind projects.
- If there already is a larger number of wind projects, one could alternatively use **existing capacity factor information** for further estimations.
- If data is not available a national **measurement campaign** may be advisable.

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Wind measurement tube towers

Source: http://www.energieprojekte.de/en/index.html

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2. FORMATION OF WIND

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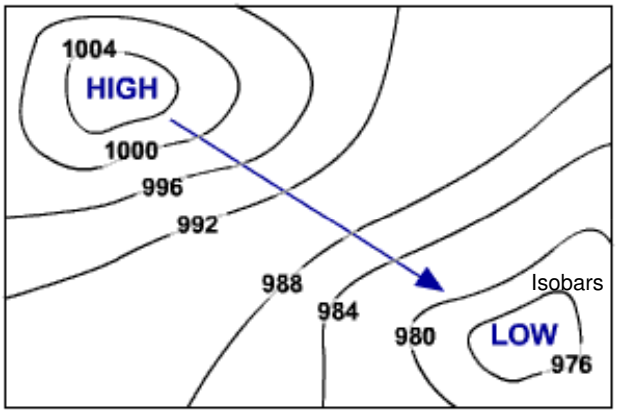
High and low pressure area

- **High pressure area** occurs when air becomes colder (winter high pressure areas can be quite strong and lasting). The air become heavier and sink towards the earth. Skies are usually clear. The airflow is clockwise (northern hemi). The air flows towards the low pressure area over the ground.



- **Low pressure** occurs when air becomes warmer. The air become lighter and rises. The pressure lowers towards the center and air flow is counterclockwise (northern hemi). Clouds will appear due to rising of the moist warm air and the weather will deteriorate. Air will flow back to the high pressure area at higher altitudes in the atmosphere.

Source: http://www.experimentalaircraft.info/weather/weather-info-1.phpar

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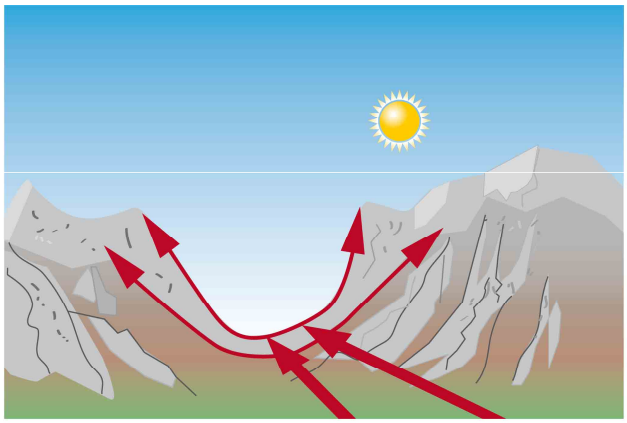
Mountain valley breeze



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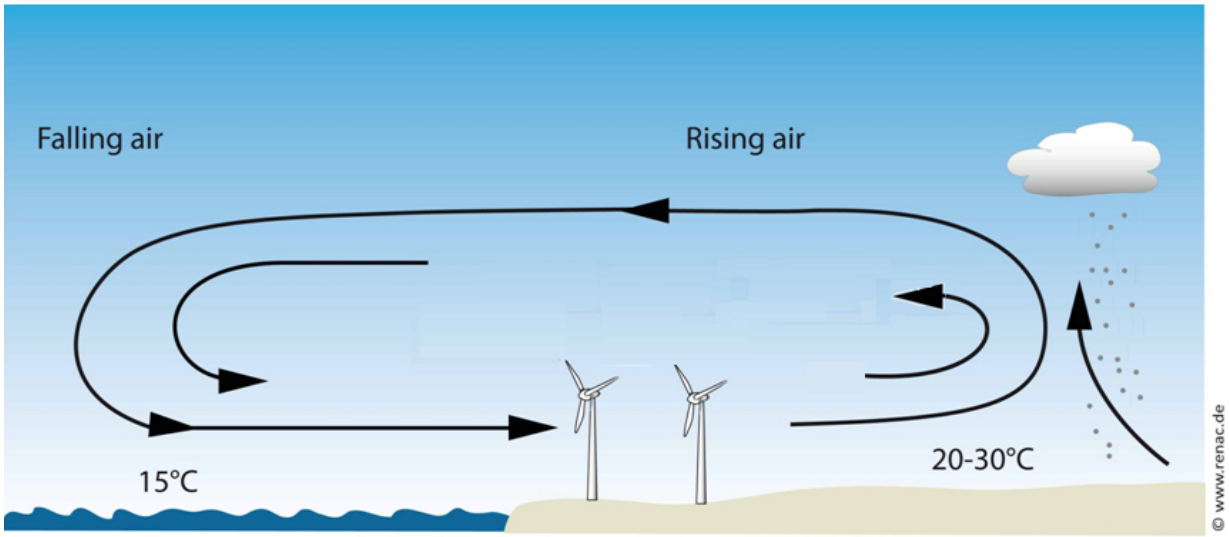
Sea-land breeze



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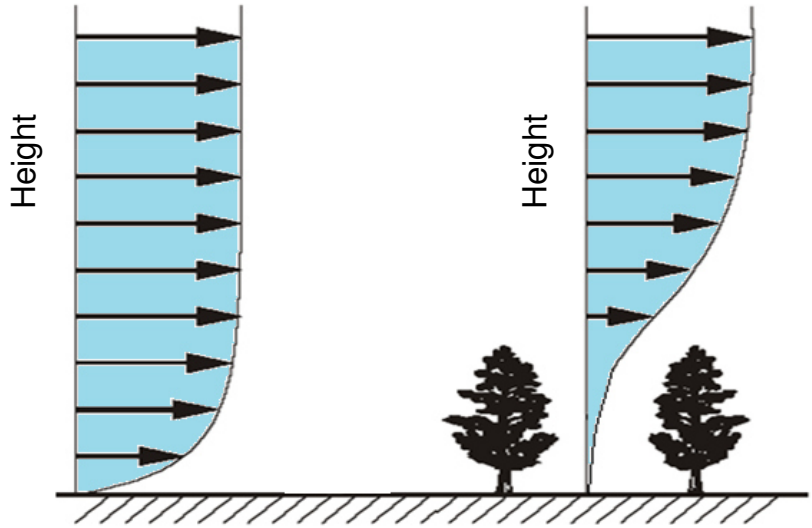
3. TECHNICAL ASPECTS WE NEED TO KNOW

Vertical wind shear profile and roughness of surface



Profile above area with low roughness (sea, low grass)

Profile above area with high roughness (forest, town)

Roughness length Z_0 and wind shear

- To evaluate wind conditions in a landscape information on the **roughness** is needed. The roughness classes or roughness lengths are **specific for different landscapes**.
- **Wind shear**: The fact that the wind profile is twisted towards a lower speed as we move closer to ground level, is usually called wind shear.

Source: http://www.windpower.org/en/core.htma

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Roughness classes and roughness lengths (European wind atlas)

Rough-ness class	Roughness length Z_0 [m]	Landscape type
0	0.0002	Water surface
0.5	0.0024	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	Agricultural land with some houses and 8 meters tall sheltering hedgerows with a distance of approx. 1250 meters
2	0.1	Agricultural land with some houses and 8 meters tall sheltering hedgerows with a distance of approx. 500 meters
2.5	0.2	Agricultural land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows with a distance of approx. 250 meters
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	Larger cities with tall buildings
4	1.6	Very large cities with tall buildings and skyscrapers

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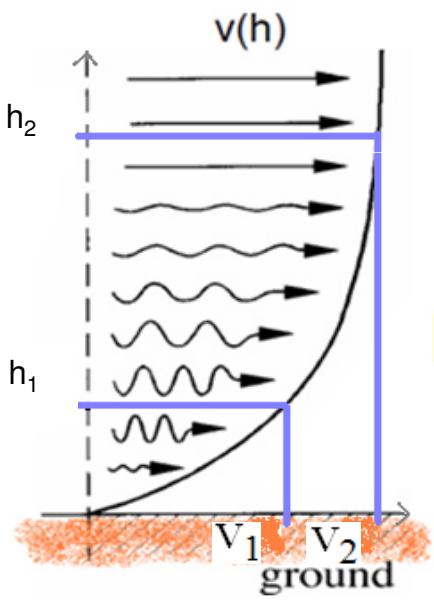
Calculating wind speed at different heights



$$v_2 = v_1 * \frac{\ln(\frac{h_2}{z_0})}{\ln(\frac{h_1}{z_0})}$$

Where:

h_1 : height [m]

h_2 : height [m]

v_1 : wind speed at h_1 [m/s]

v_2 : wind speed at h_2 [m/s]

z_0 : roughness length [m]

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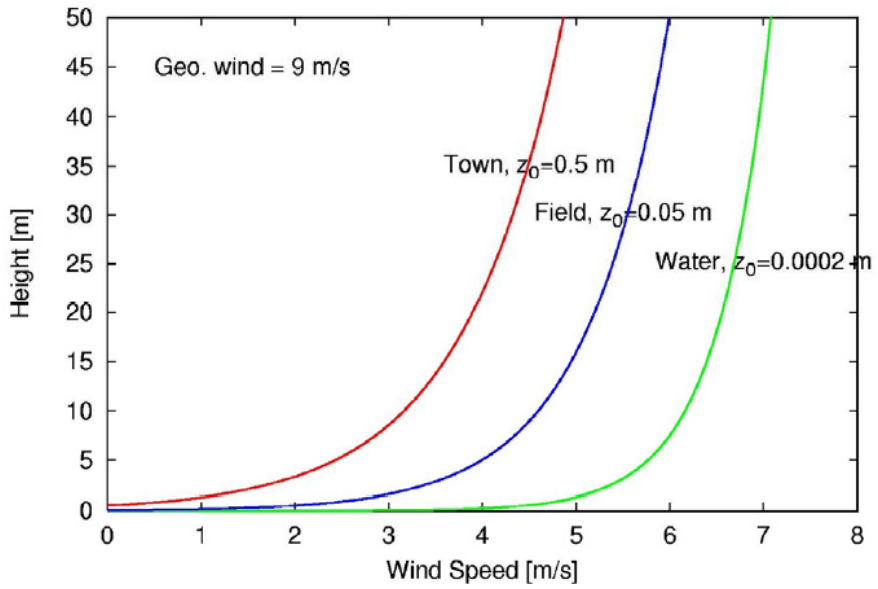
Sample wind speeds at different heights



- Wind speed increases with height above ground
- Profile depends on surface properties (roughness length, Z_0)

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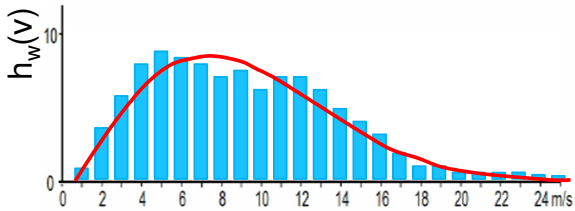
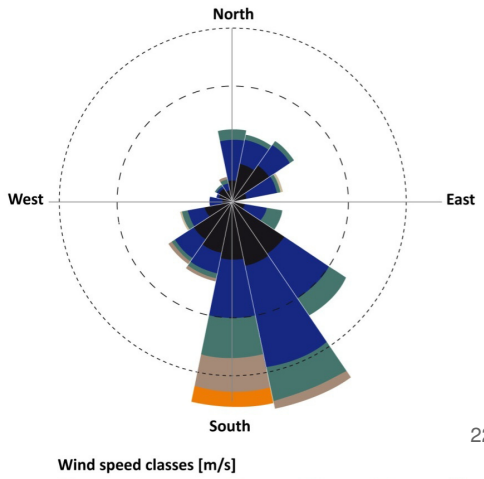
Site specific wind resource assessment for wind farm planning

- To calculate the annual energy production of a wind turbine the distribution of wind speeds is needed. It can be approximated by a Weibull equation with parameters A and K)

- The distribution of wind directions is important for the siting of wind turbines in a wind farm. The wind rose shows probability of a wind from a certain sector.
- Wind speed distributions are measured for different wind direction sectors.





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Weibull values at 50m, Canada**

Period	Mean Wind Speed	Wind Power density	Weibull shape parameter (k)	Weibull scale parameter (A)
Annual	9.22 m/s	831 W/m2	1.81	10.37 m/s
Winter (DJF)	10.43 m/s	1119W/m2	1.94	11.76 m/s
Spring (MAM)	9.03 m/s	762 W/m2	1.85	10.16 m/s
Summer (JJA)	7.86 m/s	473 W/m2	1.96	8.87 m/s
Fall (SON)	9.44 m/s	827 W/m2	1.94	10.65 m/s

**) Location: latitude = 50.853, longitude = -57.007

Source:, http://www.windatlas.ca/en/maps.php?field=E1&height=80&season=ANU

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Weibull equation factors for different regions

- For regions with similar topography the k factors are also similar
  - 1.2 < k < 1.7 Mountains
  - 1.8 < k < 2.5 Typical North America and Europe
  - 2.5 < k < 3.0 Where topography increases wind speeds
  - 3.0 < k < 4.0 Winds in monsoon regions
- Scaling factor A is related to mean wind speed (v_{avg} ~ 0,8…0,9 · A)
- Relation of mean wind v_{avg}, *k und A (*mean wind v_{avg}, *calculation)*

- **Warning: Only rough values! – On site monitoring is necessary !**

$$v_{avg} \approx A\sqrt[k]{0{,}287/k + 0{,}688^{-0{,}1}}$$

Source: J.liersch; KeyWindEnergy, 2009

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Wind measurements

- Synop measurements of meteorological stations at 10m above ground are often of limited accuracy and use for wind energy applications
- Dedicated 50m masts with at least 3 sensors at different heights are much more expensive but much better suited to derive data for wind energy.
- Most such measurements are operated privately and data may not be accessible.

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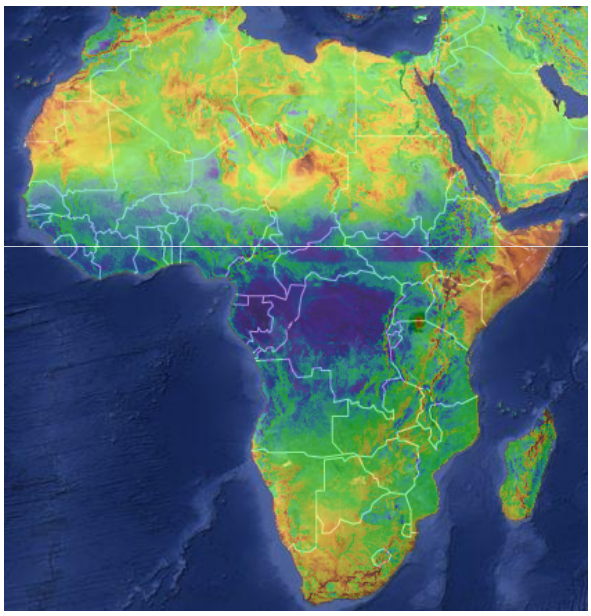
Wind Atlas based on modeling

- A suitable number of high quality measurements is characterized for its local effects
- The measurements are combined into an atlas
- Sample: 3TIER's Global Wind Dataset 5km onshore wind speed at 80m height units in m/s
- Limitations for complex terrain and costal zones



Map: IRENA Global Atlas; Data: 3TIER's Global Wind Dataset

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Power of wind

$$P = \frac{1}{2} \times \rho \times A \times v^3$$

- P = power of wind (Watt)
- ρ = air density (kg/m^3; kilogram per cubic meter)
- A = area (m^2; square meter)
- v = wind speed (m/s; meter per second)

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Quick exercise: doubling of wind speed

- Let's double the wind speed and calculate what happens to the power of the swept rotor area. Assume length of rotor blades (radius) 25 m and air density 1.225 kg/m^3).
- wind speed = 5 m wind speed = 10 m

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Solution: doubling of wind speed

- Power of swept rotor calculated with 25 m rotor radius and 1.225 kg/m^3 air density
- wind speed = 5 m/s wind speed = 10 m/s
  power = 150 kW power = 1200 kW
- **Doubling of wind speed increases power by factor 8.**

- Calculation:
  Power =0,5 * air density * (wind speed)^3 * blade length^2 * 3.1415
  Power = 0,5 * 1,225 kg/m^3 * **5**^3 m^3/s^3 * 25^2 m^2 * 3.1415 = 150 kW
  Power = 0,5 * 1,225 kg/m^3 * **10**^3 m^3/s^3 * 25^2 m^2 * 3.1415 = 1202.6 kW
  Units:[kg/m^3 * ^3 m^3/s^3 * m^2 = Joule/s = W]

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4. SPATIAL SETUP OF WIND FARMS

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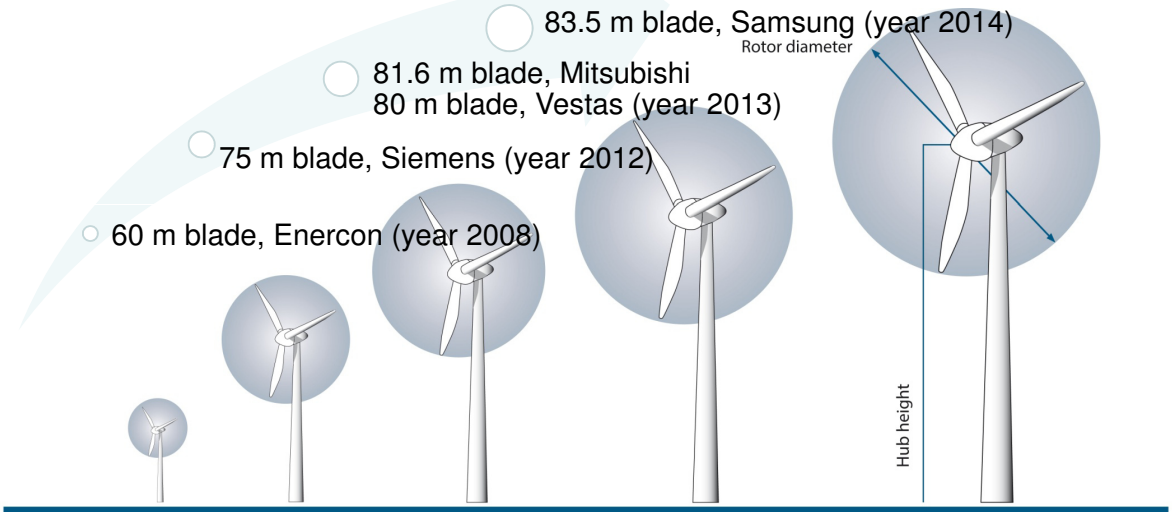
Development wind turbine rotor diameter and hub height



	1980	1985	1990	1995	2000	2005	2008	2011	2013
Rated power:	30 kW	80 kW	250 kW	600 kW	1.500 kW	3.000 kW	6.000 kW	7.500 kW	8.000 kW
Rotor diameter:	5 m	20 m	30 m	46 m	70 m	90 m	126 m	127 m	164 m
Hub height:	30 m	40 m	50 m	78 m	100 m	105 m	135 m	135 m	site specific (offshore)

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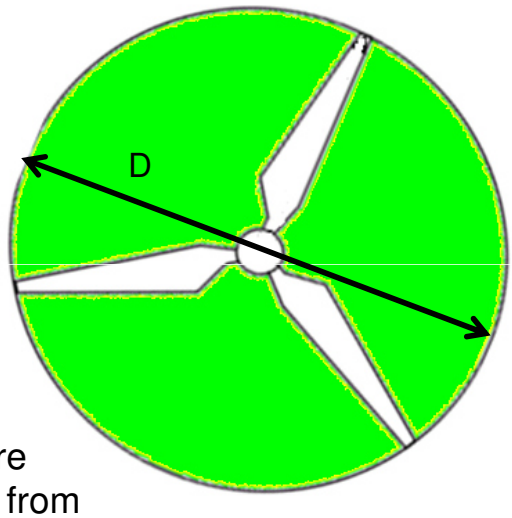
Swept area by rotor blades

$$A = \pi \times (\tfrac{1}{2} D)^2$$

- A= swept rotor area [m] ²
- D = rotor diameter [m]
- π = 3.1415



- The power output of a wind turbine is directly related to the area swept by the rotor blades. The larger the diameter of its rotor blades, the more power the wind turbine can extract from the wind. The swept area is also called the 'capture area'.

- The rotor diameter of most wind turbines is listed in specification sheets.

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Wake effect

- Clouds form in the wake of the front row of wind turbines at the Horns Rev offshore wind farm in the North Sea
- Back-row wind turbines losing power relative to the front row

Source: www.popsci.com/technology/article/2010-01/wind-turbines-leave-clouds-and-energy-inefficiency-their-wake

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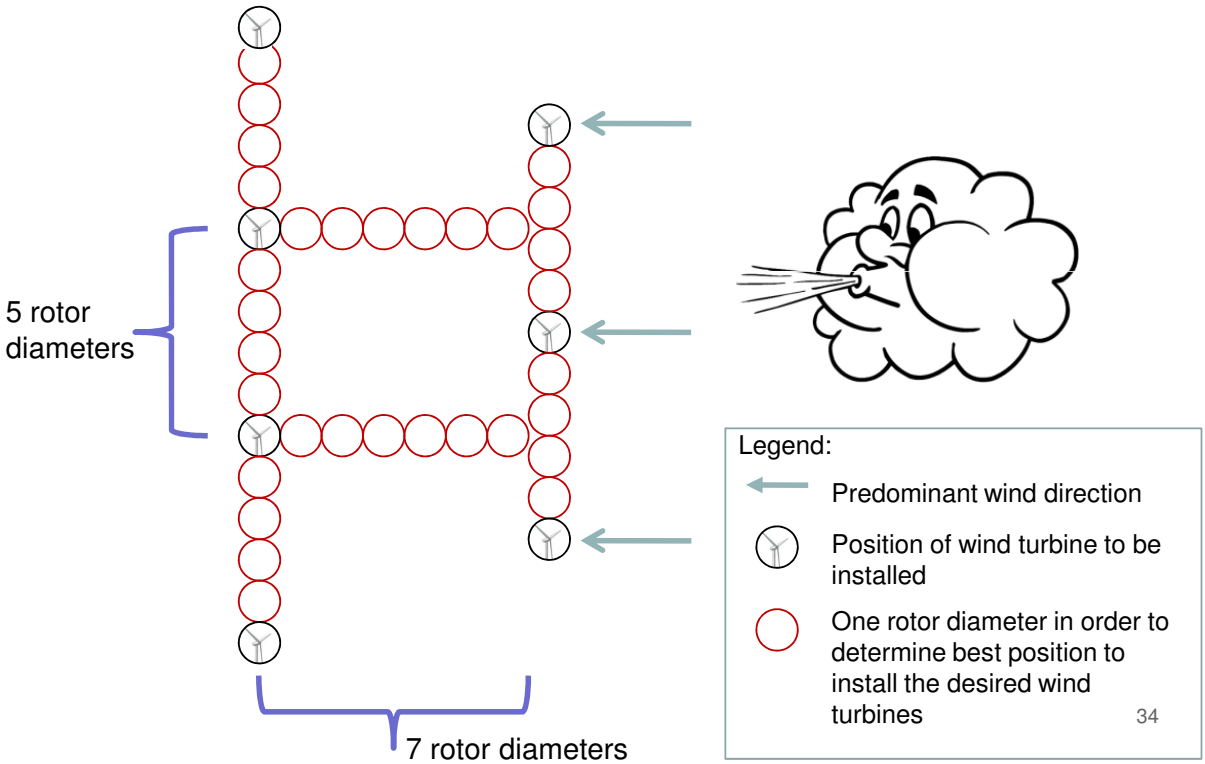
Distance between turbines to reduce wake effects



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Generator capacity, W	Rotor diameter, m	Specific capacity, W/m^2	Wind turbine manufacturer
2300	113	230	SIEMENS SWT 2,3-133
2400	117	236	Nordex N100/2400
3000	126	241	Vestas V90-2MW
3200	114	314	REPOWER 3,2M-114
2000	90	314	Vestas V126-3MW
2500	100	318	Nordex N100/2500
1500	77	322	REPOWER MD77
2300	93	338	SIEMENS SWT 2,3-93
2300	82	436	Enercon E82-2,3
3000	82	568	Enercon E82-3,0

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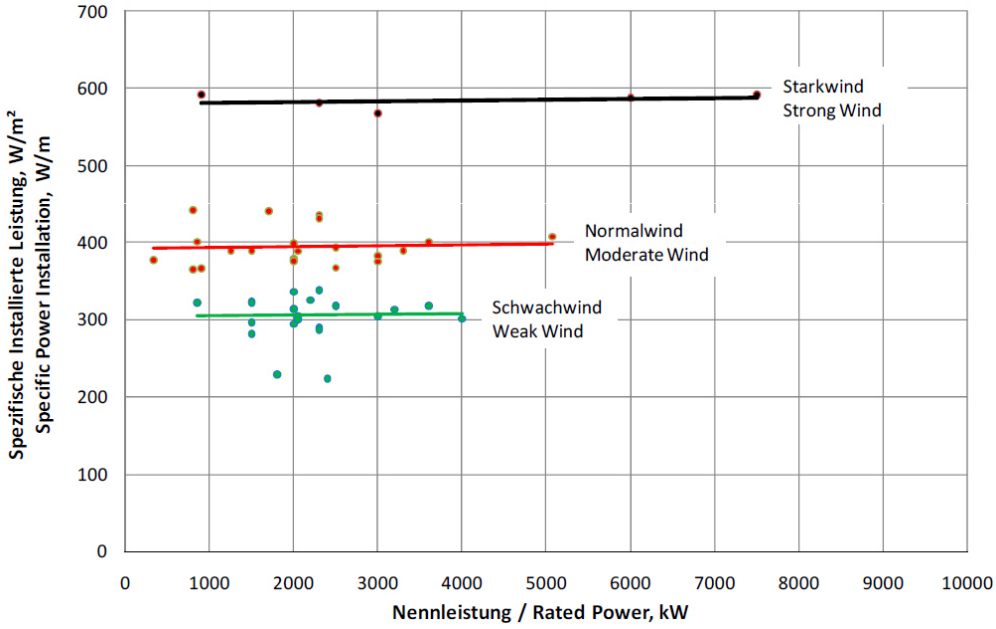
Specific power of today's wind turbines (generator capacity devided by sweapt rotor area)



Source: Molly, 2011

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Wind power capacity and annual energy generation estimation for an area e.g. with 25 km²

Rated power of wind turbine, MW	2	3	2	2,5	2,35	2,3	3
Rotor diameter of wind turbine, m	114	126	90	100	92	82	82
Specific rated power per swept rotor area (W/m^2)	196	241	314	318	354	436	568
Specific wind power capacity per land area, MW/ km^2; ***)	4,40	5,40	7,05	7,14	7,93	9,77	12,75
Number of turbines in the area	55	45	88	71	84	106	106
Installed wind power capacity, MW	110	135	176	179	198	244	319
Annual energy production with capacity factor of 0,35; GWh/a	337	414	541	548	608	749	977

***) Assumptions: distance between wind turbines standing in main wind direction:7 rotor diameter; and standing in in rarely ocurring perpendicular wind direction: 5 times the rotor diameter

Source: RENAC calculation

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5. ESTIMATING WIND ELECTRICITY YIELD

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What needs to be done

1. Define a representative mix of suitable turbines (potenitally site-specific).
2. Get power curve information for all turbine types.
3. Extrapollate average wind speeds to applicable hub heights.
4. Choose the wind speed distribution curve which is most likely at given sites(s).
5. Calculate wind speed distributions for given hub heights.

6. Use wind speed distributions and power curves to calclulate representative wind energy yield(s).

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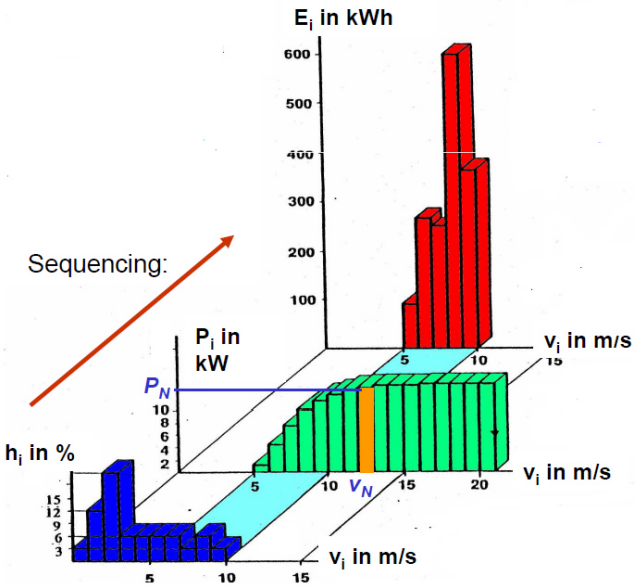
Calculation scheme for wind energy yield using wind speed distributions and power curves

- E_i = Annual energy yield of wind class [Wh, watthours], i = 1, 2, 3 …n
- t_i = duration of wind speeds at wind class [h/a hours/year]
- $P_i(v_i)$ = Power of wind class v_i of wind turbine power curve [Watt]
- v_i = wind class [m/s]
- PN = Nominal power of WEC [kW] at nominal wind class v_i [m/s]
- h_i = relative wind class frequency in %



Source: J.liersch; KeyWindEnergy, 2009

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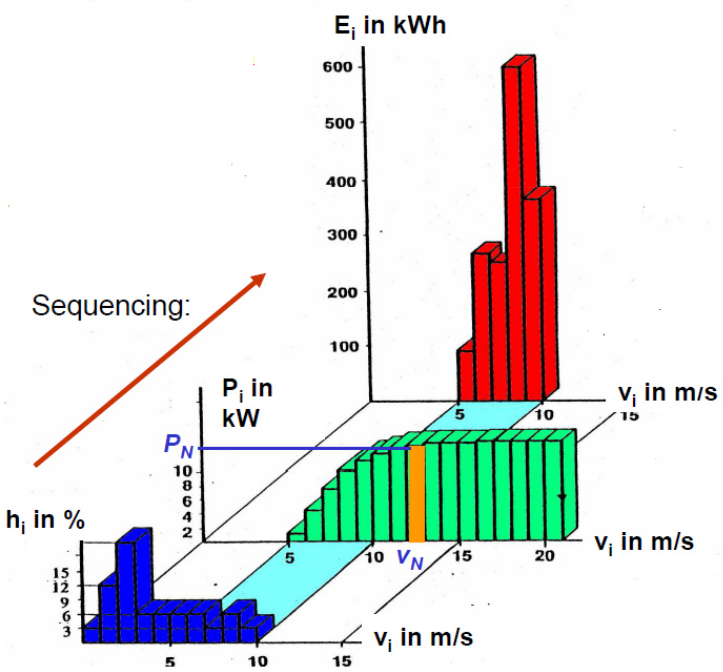
Calculation scheme for annual energy production



$E_i = P_i(v_i) * t_i$

$E_\Sigma = E_1 + E_2 + \ldots + E_n$

- E_Σ = Energy yield over one year

J.liersch; KeyWindEnergy, 2009

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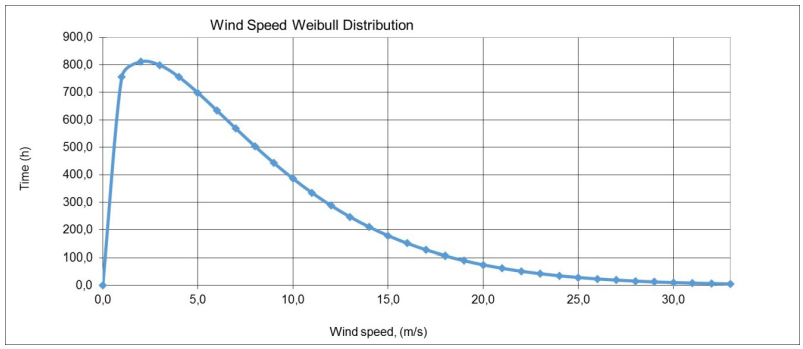
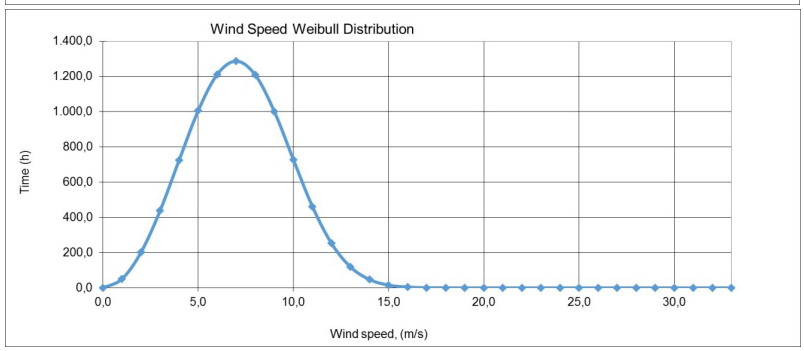
Shape of different wind speed distributions

- Weibull distribution: shape factor k=1,25 and A= 8 m/s



- Weibull distribution: shape factor k=3 and A= 8 m/s



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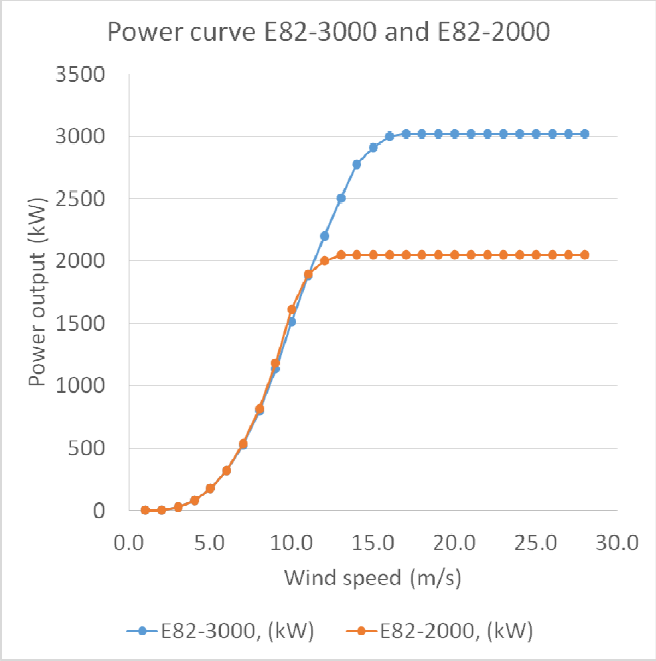
Sample power curves of wind turbines (82 m rotor diameter, 2 and 3 MW)



Source: Enercon product information 2014

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Worked example

6. ESTIMATING WIND CAPACITY AND YIELD AT A GIVEN SITE

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Wind energy yield estimation near Arusha

- Steps performed:
  1) Retrieve average wind speed data from Global Atlas
  2) Estimate electricity yield of one wind turbine
  3) Estimate wind power capacity and potential wind energy per km² at given location

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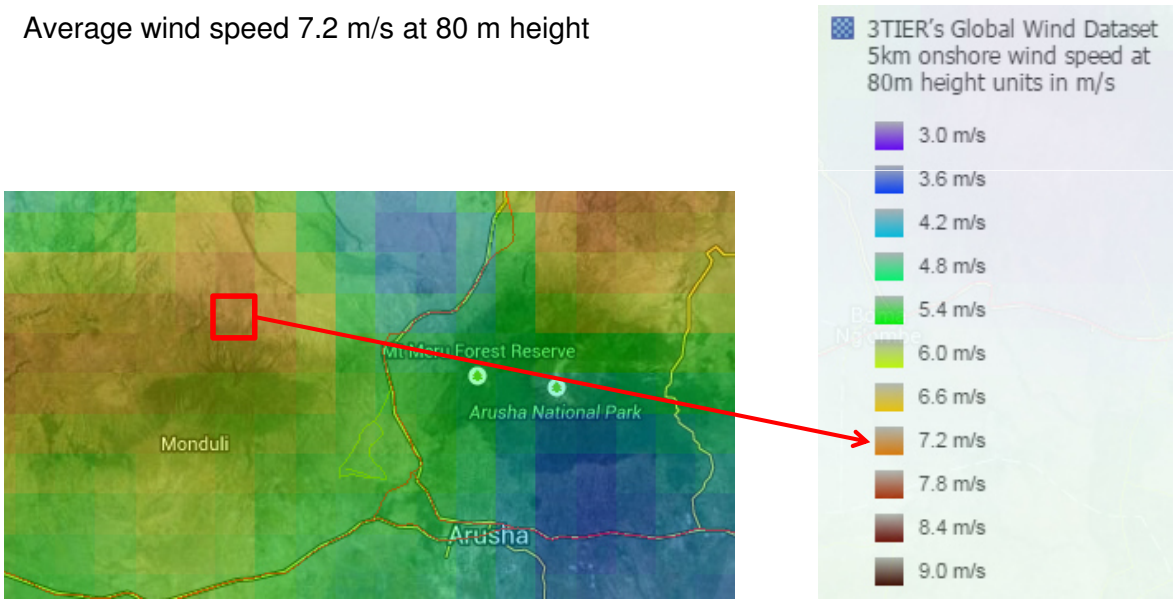
Retrieving average wind speed

- Average wind speed 7.2 m/s at 80 m height



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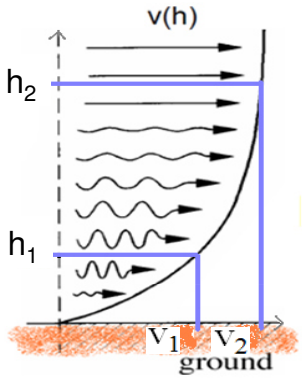
Extrapolation to hub height



- Wind data provided for height: h_1 = 80 m
- Let's choose hub height: h_2 = 90 m
- Roughness length: z_0 = 0.1m

- Result: v_2 = 7.3 m/s

Rough - ness class	Roughness length Z_0 [m]	Landscape type
2	0.1	Agricultural land with some houses and 8 meters tall sheltering hedgerows with a distance of approx. 500 meters

$$v_2 = v_1 * \frac{\ln(\frac{h_2}{z_0})}{\ln(\frac{h_1}{z_0})}$$

Where:
h_1 : height [m]
h_2 : height [m]
v_1 : wind speed at h_1 [m/s]
v_2 : wind speed at h_2 [m/s]
z_0 : roughness length [m]

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Estimating wind speed distribution

- Deriving Weibull distribution
  - Average wind speed: $v_2 = v_{avg}$ = 7.2 m/s
  - Assumption: monsoon climate → k = 3.5
  - Scaling factor: $v_{avg} = 0.9 * A \rightarrow A = v_{avg} / 0.9$
    $A = (v_{avg} / 0.9) = (7.3 \text{ m/s}) / 0.9 = 8.11 \text{ m/s}$

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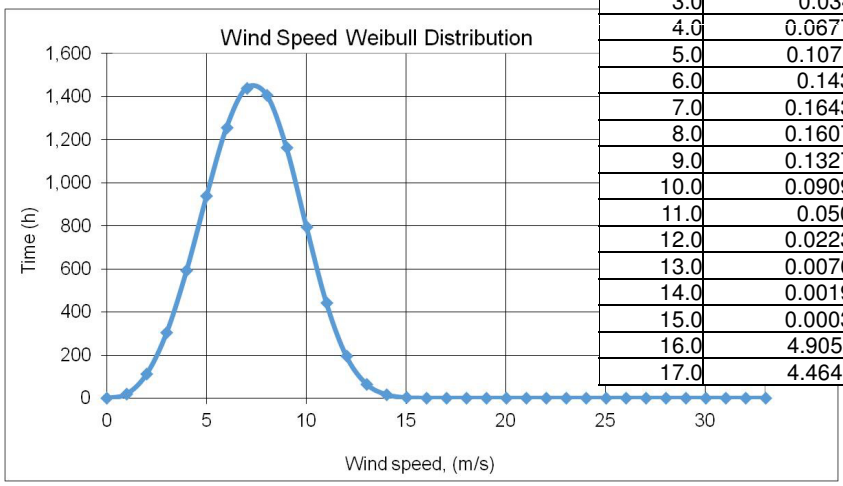
Resulting wind distribution



v_i (m/s)	Weibull probability (%)	number of hours at v_i m/s per year
0.0	0	0.0
1.0	0.002301447	20.2
2.0	0.012930901	113.3
3.0	0.03481178	305.0
4.0	0.067742212	593.4
5.0	0.107112259	938.3
6.0	0.14337442	1,256.0
7.0	0.164325824	1,439.5
8.0	0.160762789	1,408.3
9.0	0.132719153	1,162.6
10.0	0.090914034	796.4
11.0	0.05061706	443.4
12.0	0.022370894	196.0
13.0	0.007647482	67.0
14.0	0.001966378	17.2
15.0	0.000369182	3.2
16.0	4.90543E-05	0.4
17.0	4.46477E-06	0.0

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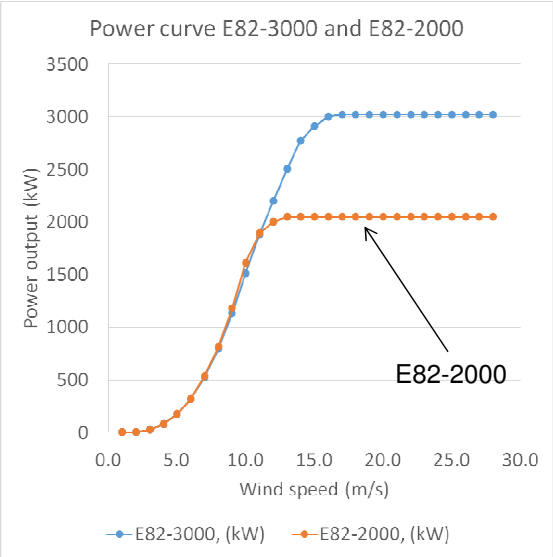
Choosing the wind turbine

- We choose enercon E82-2000



v_i (m/s)	Output power of E82-2000, (kW)
0.0	
1.0	0
2.0	3
3.0	25
4.0	82
5.0	174
6.0	321
7.0	532
8.0	815
9.0	1180
10.0	1612
11.0	1890
12.0	2000
13.0	2050
14.0	2050
15.0	2050
16.0	2050
17.0	2050

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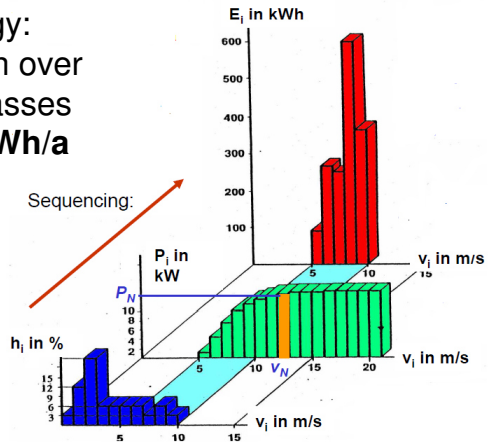
Calculate power output per wind speed class

v_i (m/s)	number of hours at v_i m/s per year	Output power of E82-2000, (kW)	E82-2000, annual energy yield, (kWh/a)
0.0	0.0		
1.0	20.2	0	0
2.0	113.3	3	340
3.0	305.0	25	7,624
4.0	593.4	82	48,661
5.0	938.3	174	163,265
6.0	1,256.0	321	403,163
7.0	1,439.5	532	765,811
8.0	1,408.3	815	1,147,750
9.0	1,162.6	1180	1,371,891
10.0	796.4	1612	1,283,808
11.0	443.4	1890	838,036
12.0	196.0	2000	391,938
13.0	67.0	2050	137,333
14.0	17.2	2050	35,312
15.0	3.2	2050	6,630
16.0	0.4	2050	881
17.0	0.0	2050	80

Example:
@ v=7.0 m/s:
1,439.5 h/a * 532 kW = 765,811 kWh/a

Total energy:
Summation over all wind classes
= **6.603 MWh/a**



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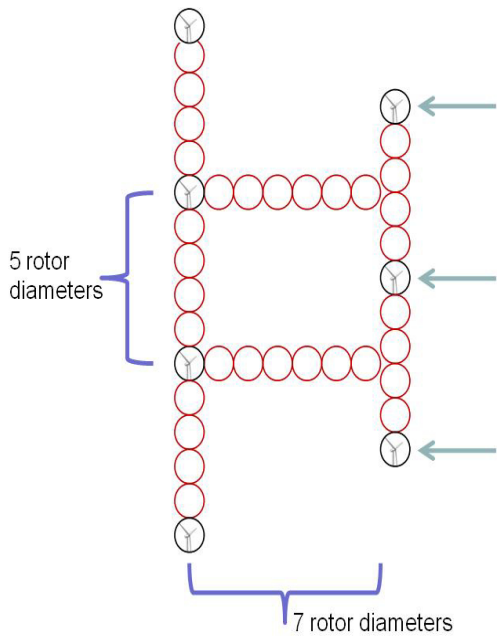
Estimating capacity per km²

- Rotor diameter d=82 m
- Distance d_1 primary wind direction:
  7 rotor diameters = 7 * 82 m = 574 m
- Distance d_2 secondary wind direction:
  5 rotor diameters = 5 * 82 m = 410 m
- Area needed for one turbine:
  574 m * 410 m = 235,340 m² = 0.24 km²
- Capacity per km²:
  2 MW/0.24 km² = **8.3 MW/km²**



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Estimating energy per km² and capacity factor

- Capacity per km²:
  2 MW/0.24 km² = 8.3 MW/km²
- Energy generation per wind turbine:
  6,603 MWh per turbine (E82-2000) with 2 MW rated capacity,
  OR: 6,603 MWh / 2 MW → 3,302 MWh / 1 MW
- Energy generated per km²:
  3,302 MWh/MW * 8.3 MW/km² = **27,4 GWh/km²/a**

- Capacity Factor: 3,302 MWh / 1 MW = 3,302 h
  3,302 h / 8,760 h = **37.7%**

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Please remember

- The previous worked example is only a rough estimate and results are only true for the given assumptions (specific site, one turbine type, wind distribution assumptions, etc.)
- The calculated energy yield should be considered as ideal result. In real-life power output is likely to be slightly below these values due to downtimes (maintenance, grid outages), cabling and transformation losses, deviation from ideal distribution of wind turbines on the given site, etc.

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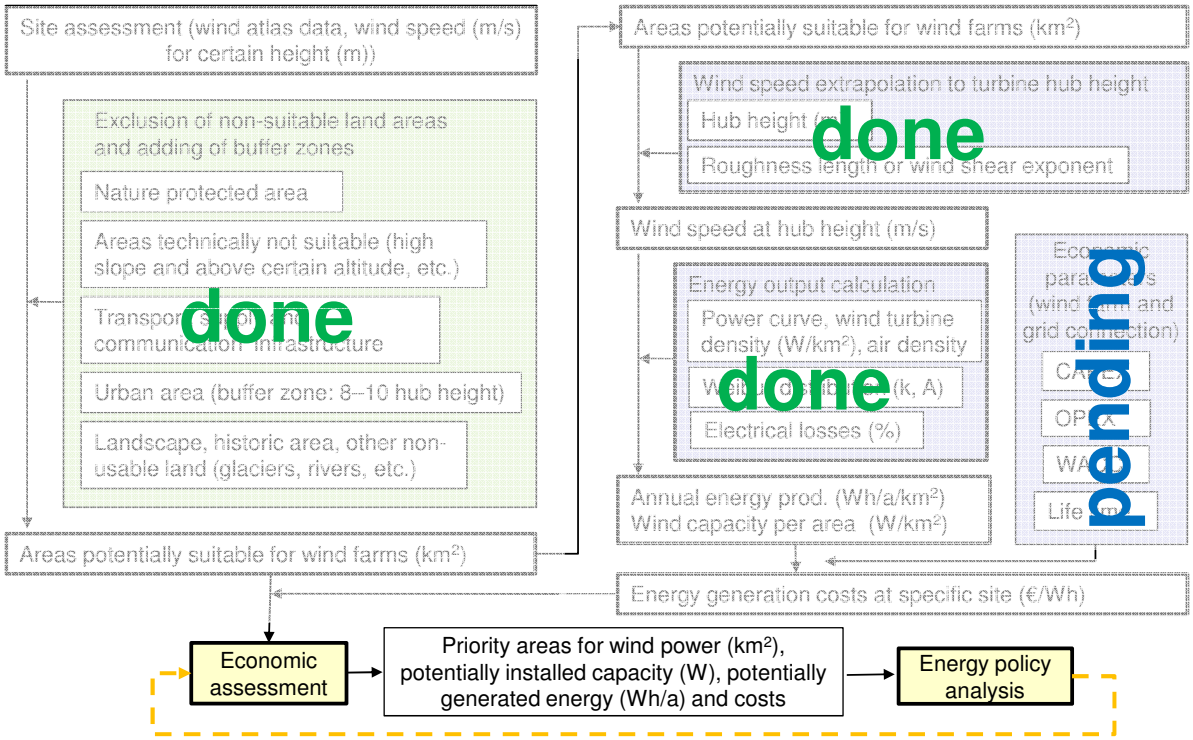

CAPEX = Capacity expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (depth, equity)

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Thank you very much for your attention!

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