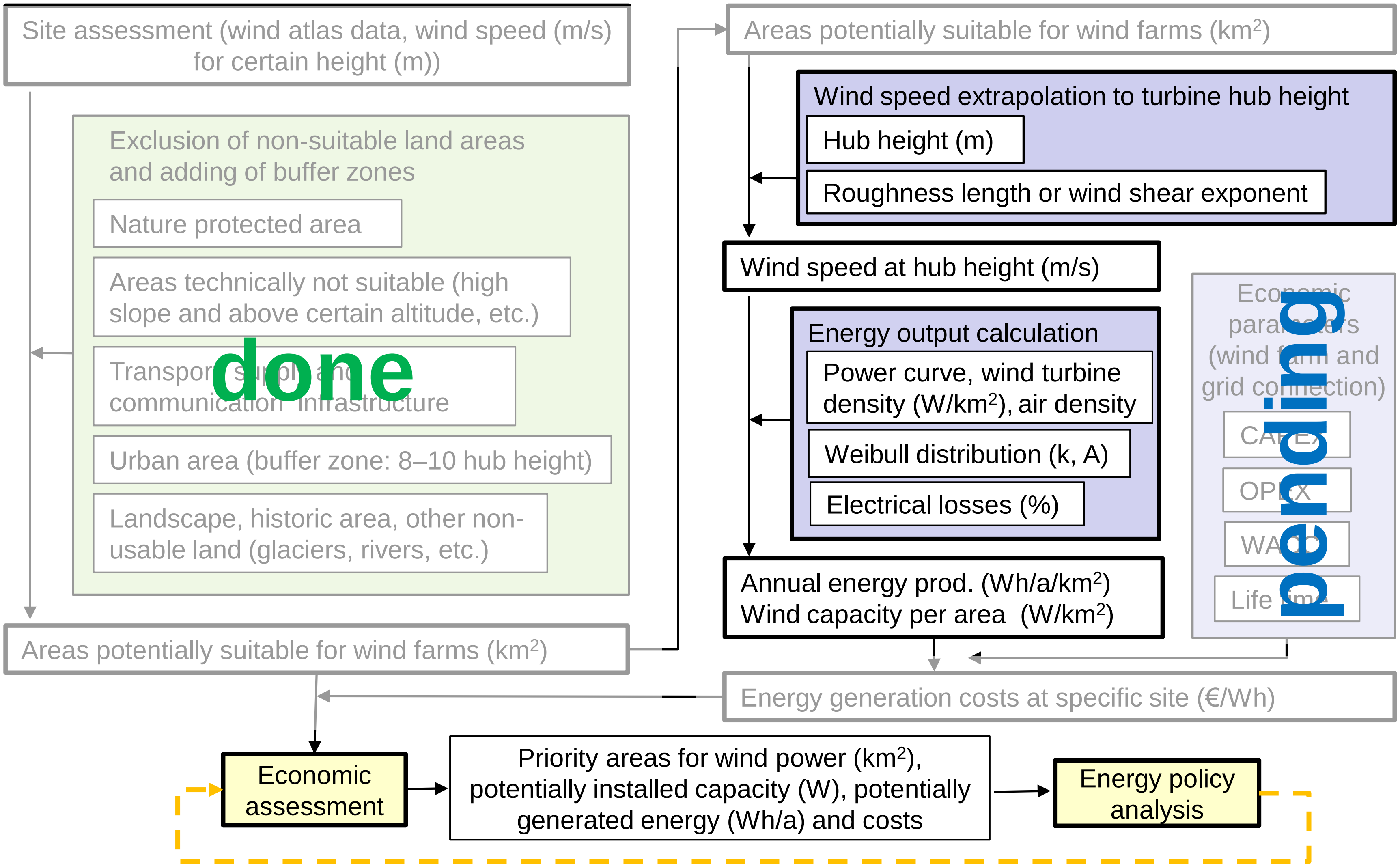
Session 2a:
Wind power spatial planning techniques

IRENA Global Atlas
Spatial planning techniques
2-day seminar

Central questions we want to answer

- After having identified those areas which are potentially available for renewables, we want to estimate…
  - what the potential **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.



CAPEX = Capital expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (debt, equity)

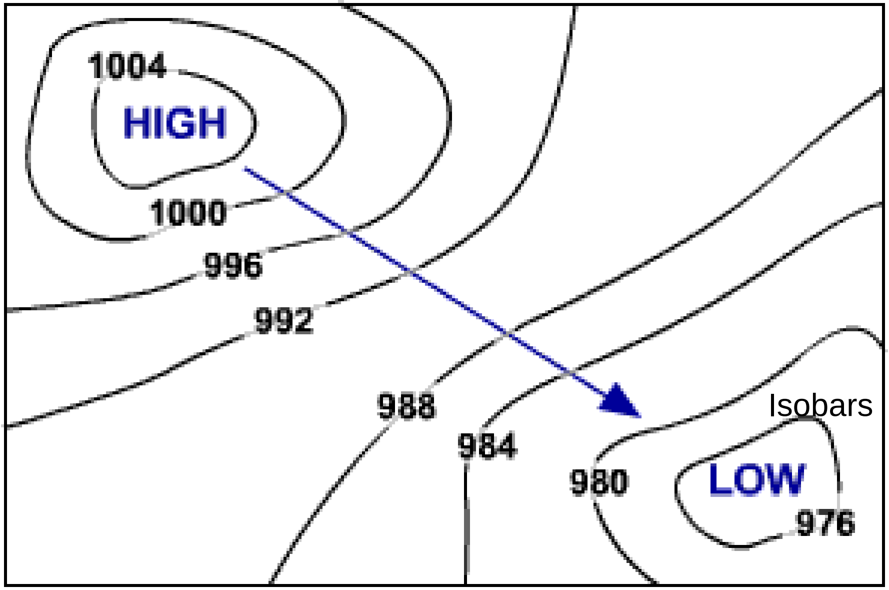
Agenda

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

1. FORMATION OF WIND

High and low pressure area

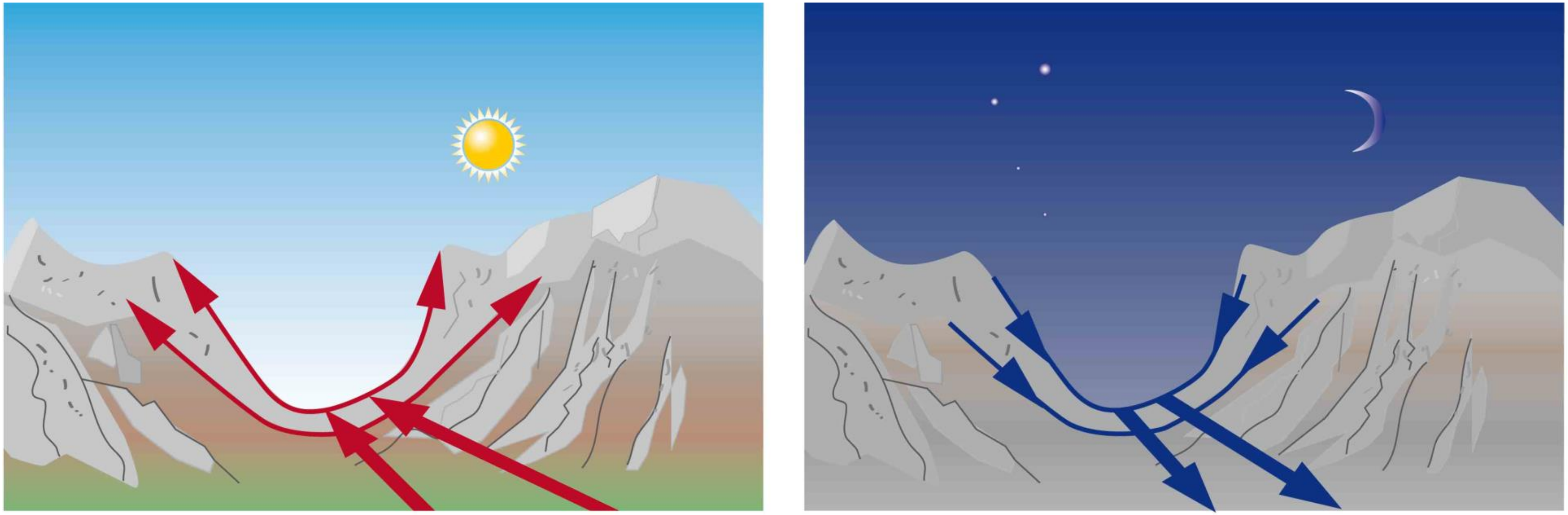
- **High pressure area** occurs when air becomes colder (winter high pressure areas can be quite strong and lasting). The air becomes heavier and sinks towards the earth. Skies are usually clear. The airflow is clockwise (northern hemi). The air flows towards the low pressure area over the ground.



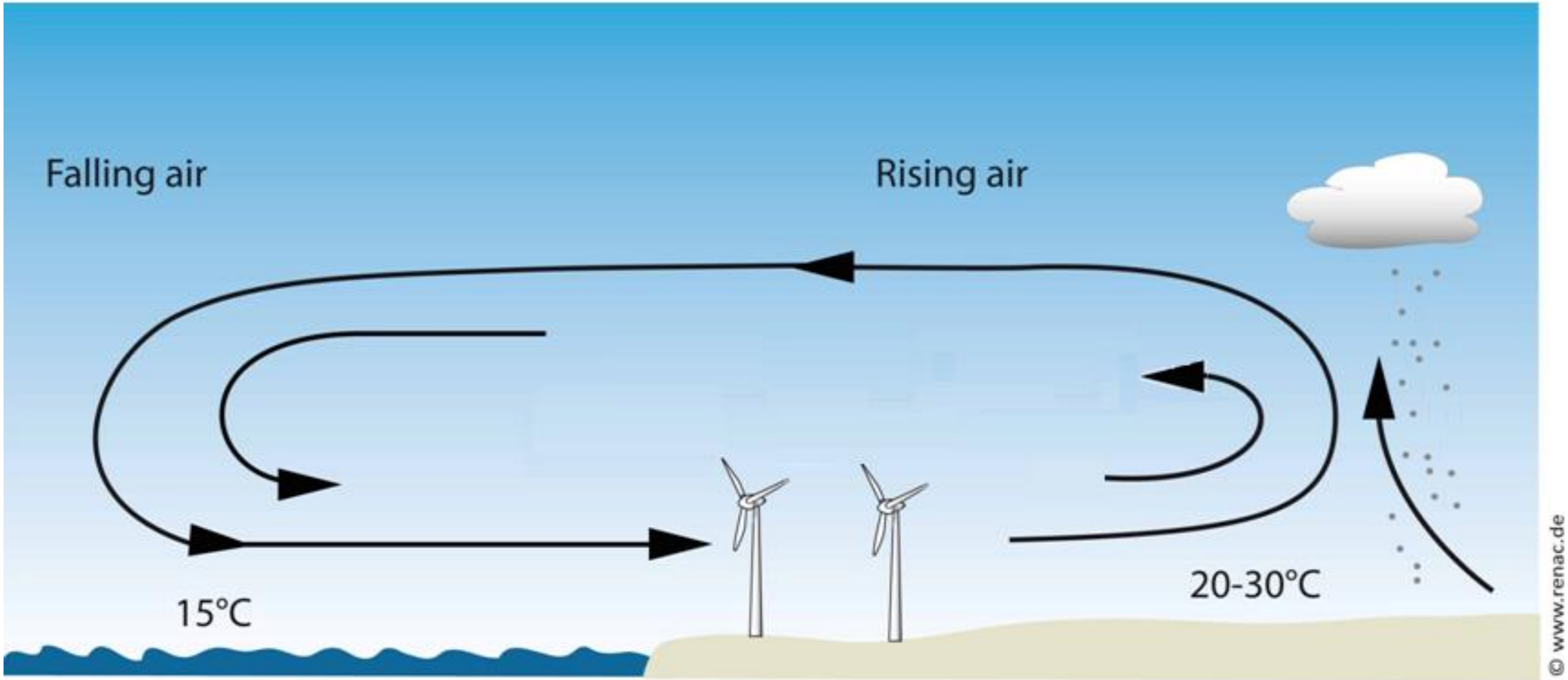
- **Low pressure** occurs when air becomes warmer. The air becomes lighter and rises. The pressure lowers towards the center and air flow is counterclockwise (northern hemi). Clouds will appear due to rising of the moist warm air and the weather will deteriorate. Air will flow back to the high pressure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

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

Mountain valley breeze

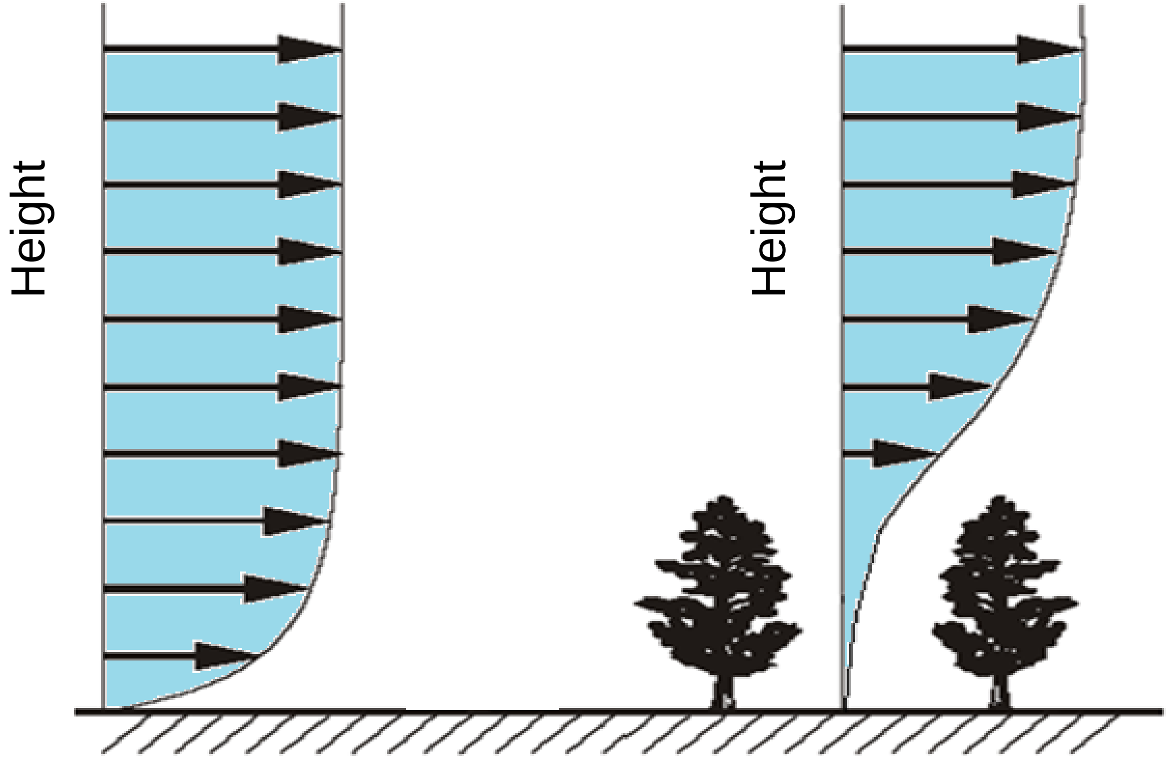


Sea-land breeze



2. TECHNICAL ASPECTS WE NEED TO KNOW

Vertical wind shear profile and roughness of surface



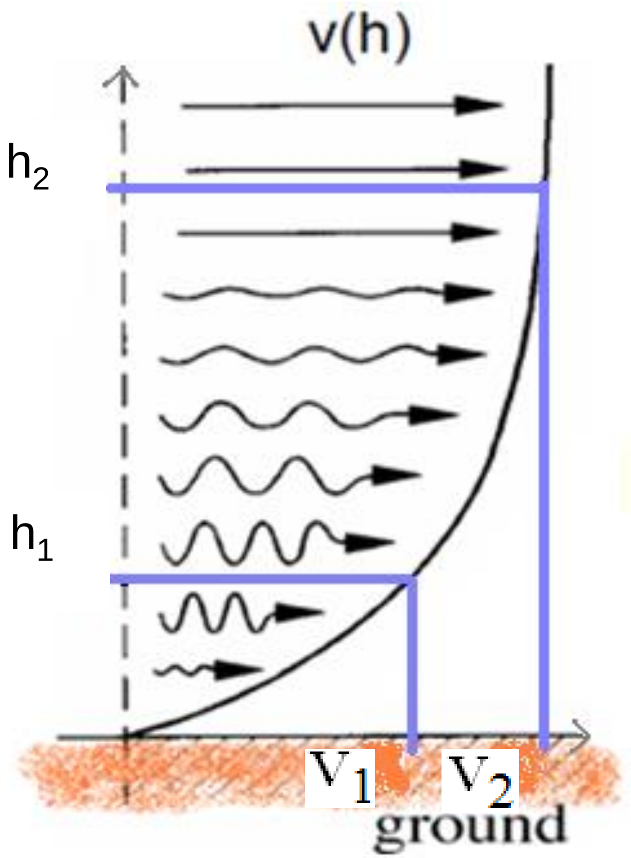
Profile above area with low roughness (sea, low grass)

Profile above area with high roughness (forest, town)

Roughness 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

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]

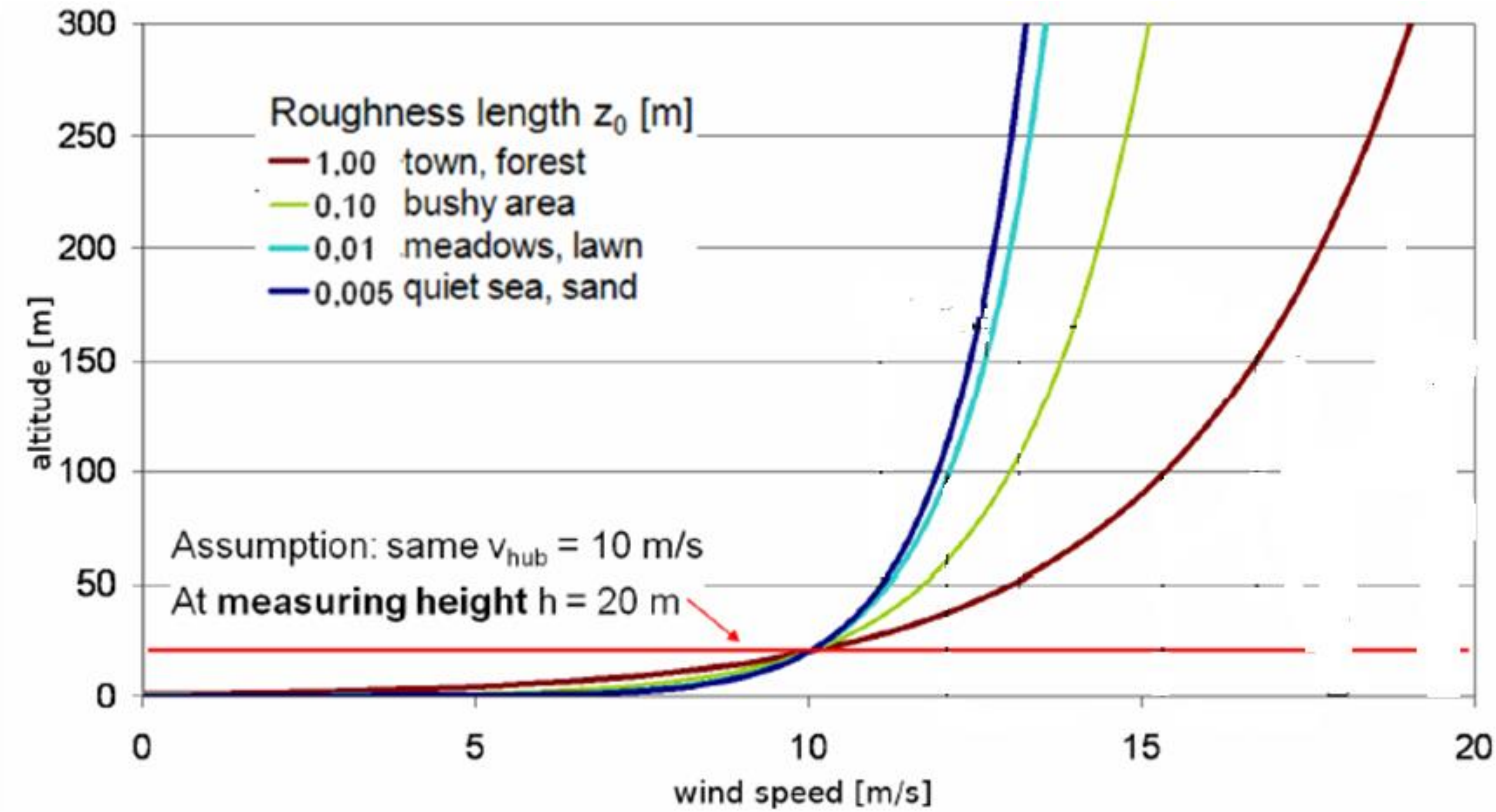
h_2 : height [m]

v_1 : wind speed at h_1 [m/s]

v_2 : wind speed at h_2 [m/s]

z_0 : roughness length [m]

Schematic wind shear for different roughness classes - wind speed measured at the same height

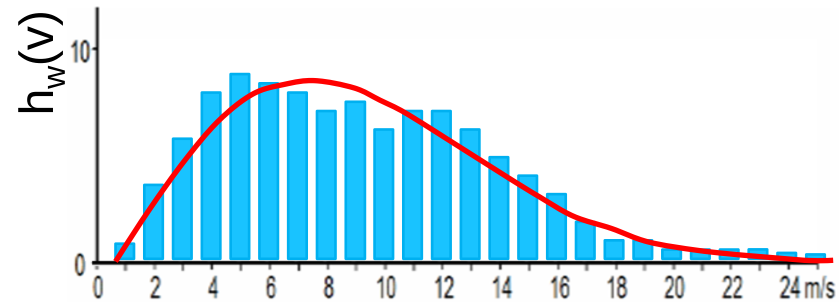


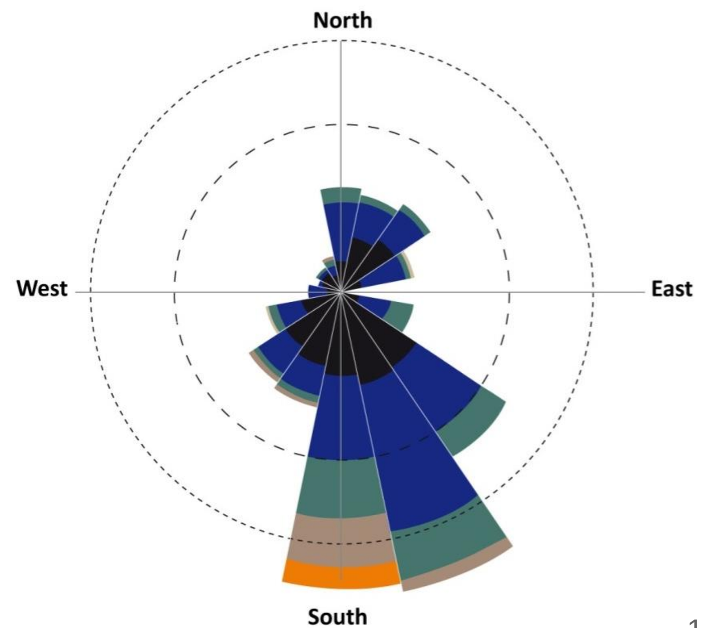
J.liersch; KeyWindEnergy, 2009

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.





Wind speed classes [m/s]

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 e.g. monsoon regions
- Scaling factor A is related to mean wind speed ($v_{avg} \sim 0{,}8 \ldots 0{,}9 \cdot A$)
- Relation of mean wind v_{avg}, *k und A* (mean wind v_{avg}, *calculation)*

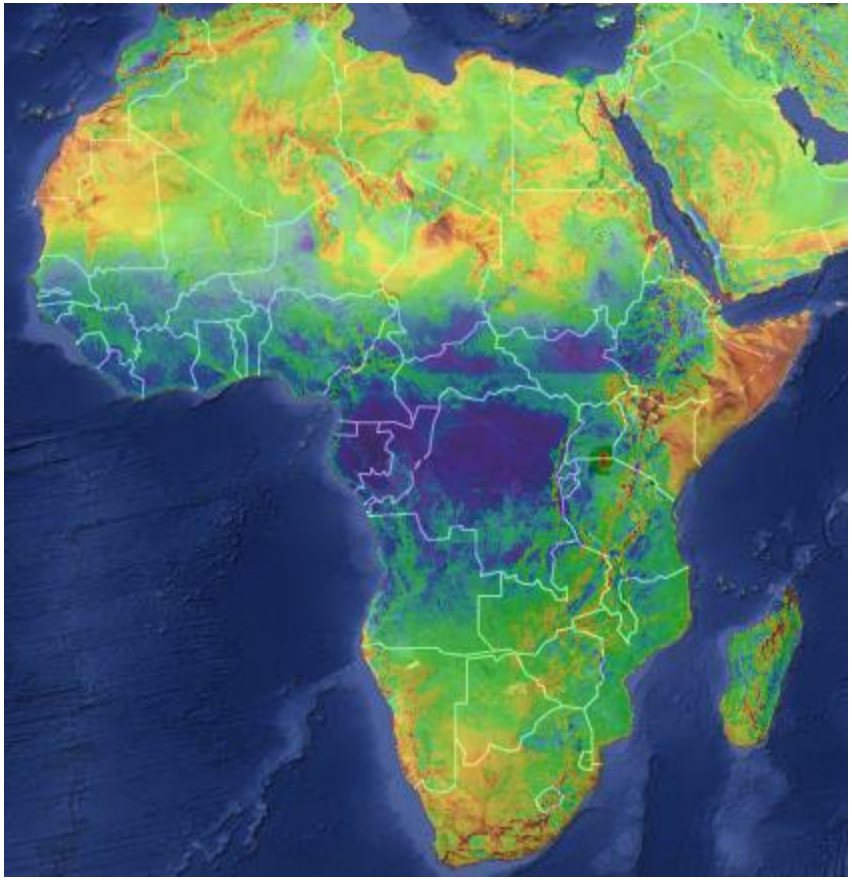
- **Warning: Only rough values! – On site monitoring is necessary !**

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

Source: J.liersch; KeyWindEnergy, 2009

Wind Atlas based on modelling

- 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

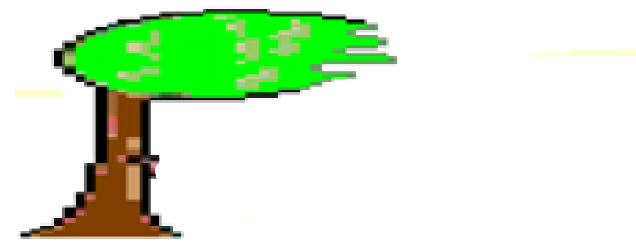
Power of wind

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

- 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)

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



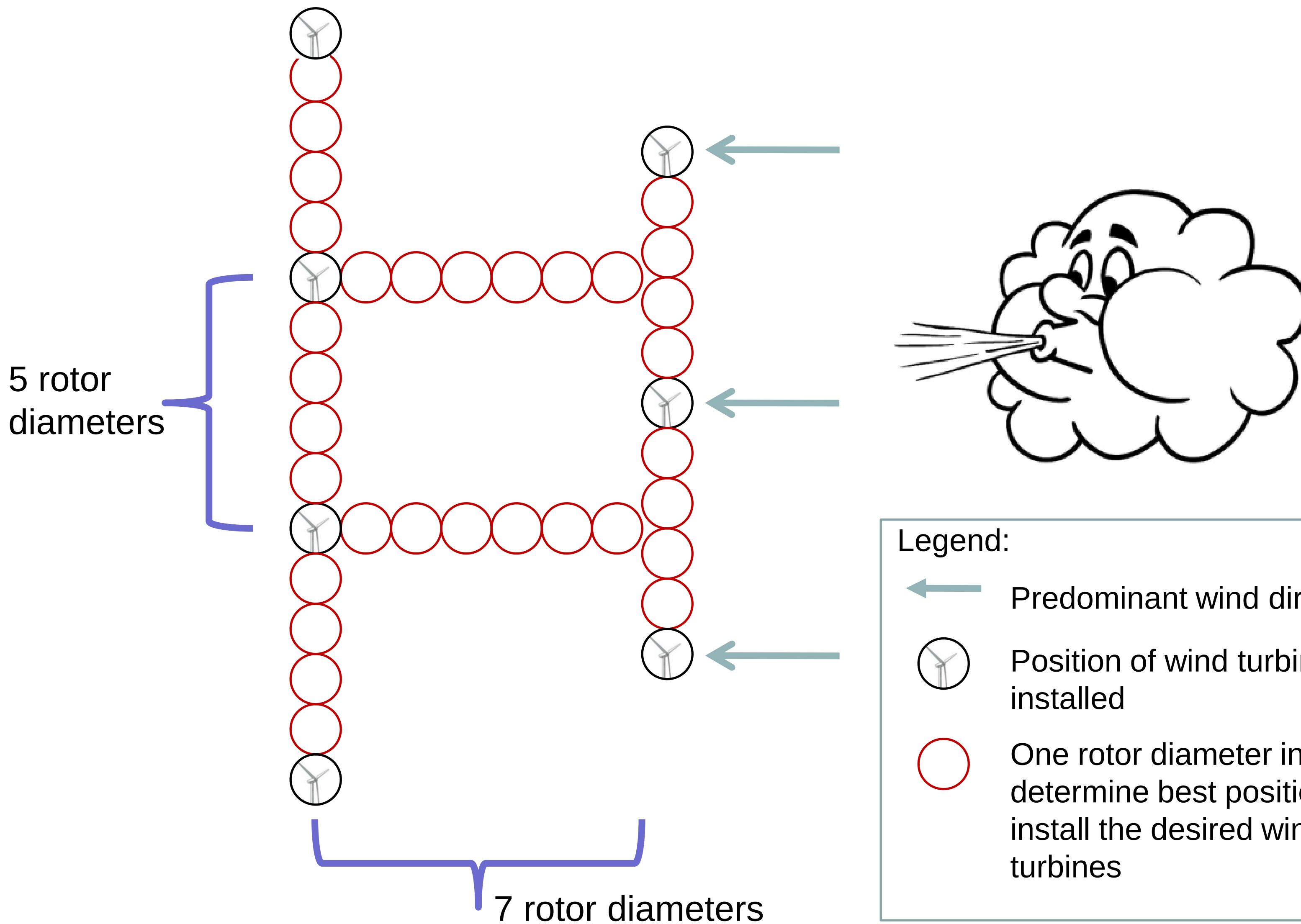
3. SPATIAL SETUP OF WIND FARMS

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 renac renewables academy · IET International Energy Transition · IRENA International Renewable Energy Agency

Distance between turbines to reduce wake effects



Legend:

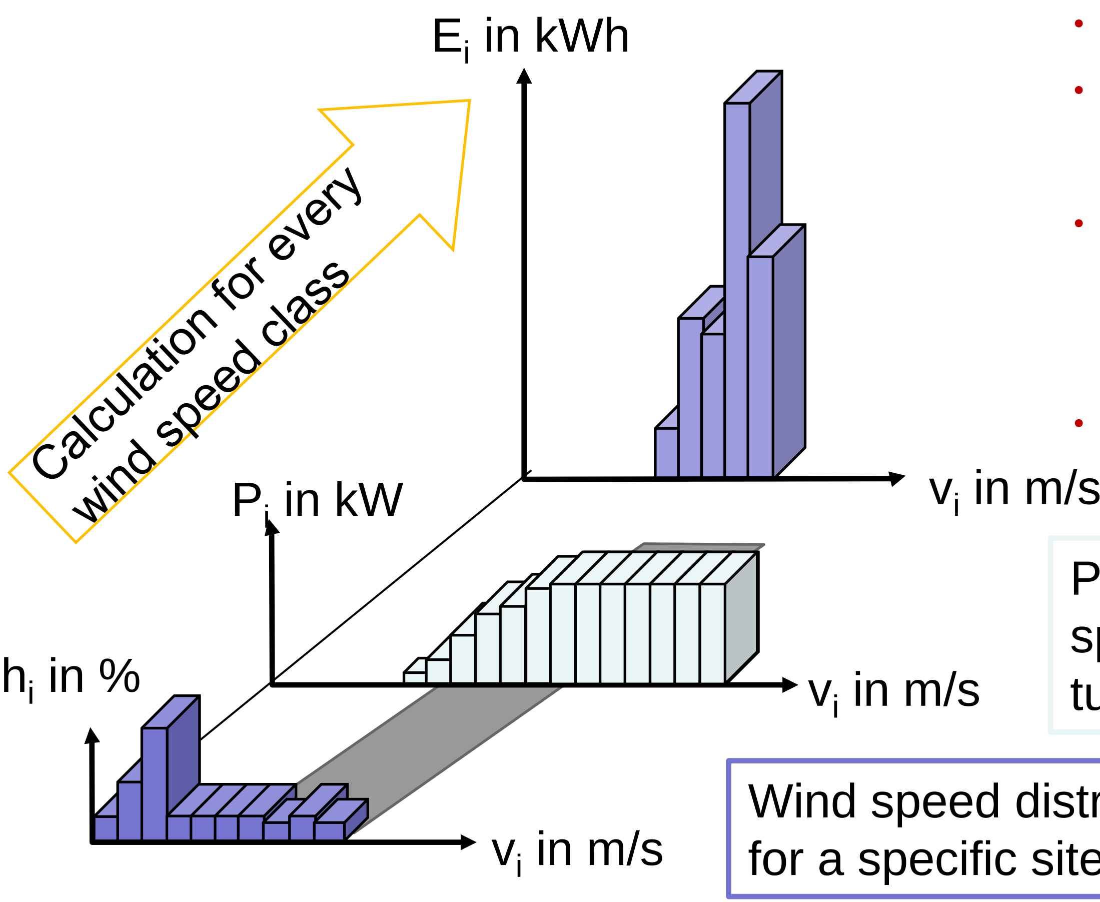
- Predominant wind direction
- Position of wind turbine to be installed
- One rotor diameter in order to determine best position to install the desired wind turbines

4. ESTIMATING WIND ELECTRICITY YIELD

What needs to be done

1. Define a representative mix of suitable turbines (potentially 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 site(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).

Wind energy yield calculation



- v_i = wind speed class i [m/s]
- h_i = relative frequency of wind speed class in %
- P_i = power output of wind turbine at wind speed class v_i [kW]
- E_i= energy yield of wind speed class i [kWh]

Power curve of a specific wind turbine

Wind speed distribution for a specific site

Annual energy production of a wind turbine

$$E_i = P_i \times t_i$$

E_i = energy yield of wind class, i = 1, 2, 3 …n
[Wh, watthours]

t_i = duration of wind speeds at wind class
[h/a, hours/year]

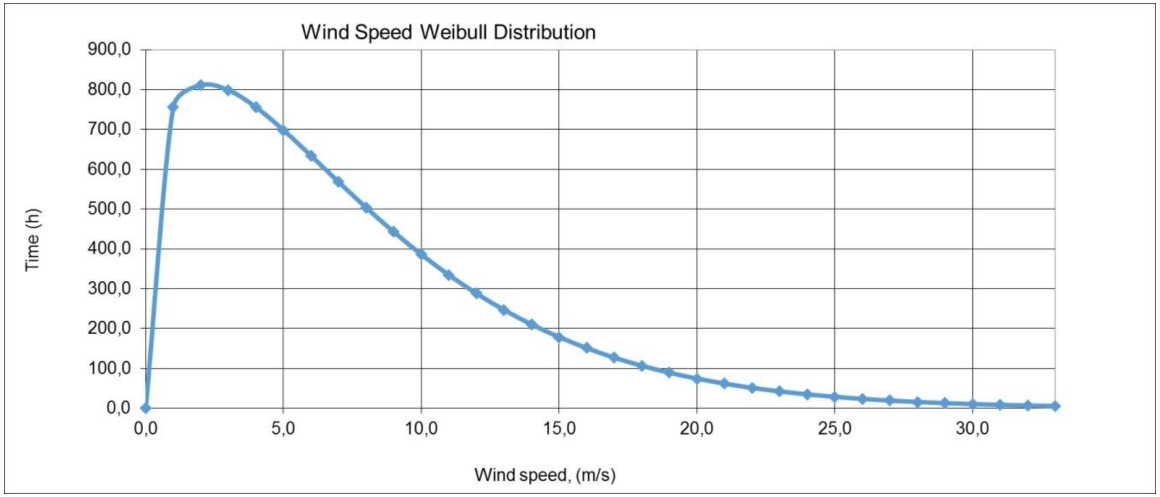
P_i = power of wind class vi of wind turbine power curve
[Watt, joule per second]

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

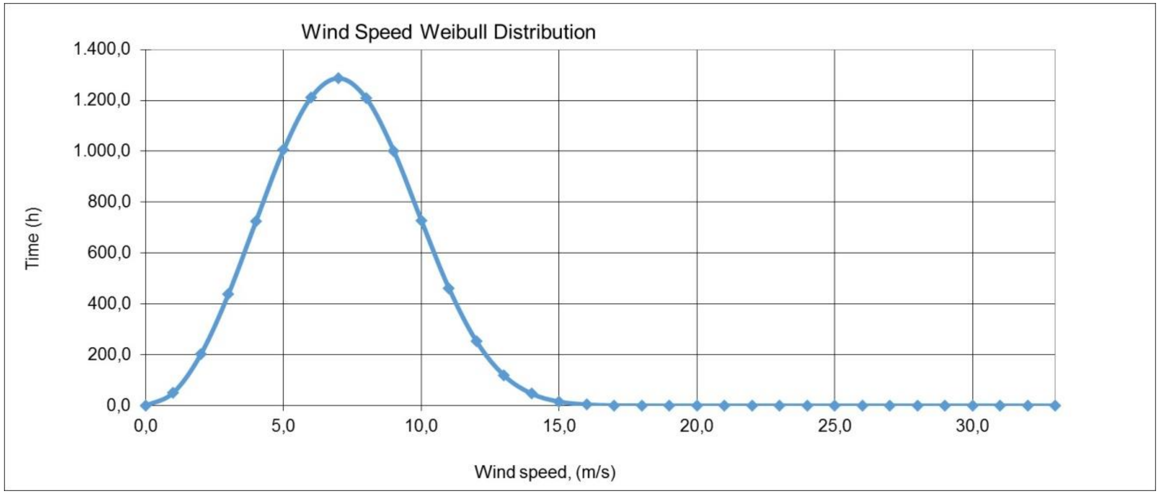
E_Σ = energy yield over one year [Wh/a, watthours / year]

Shape of different wind speed distributions

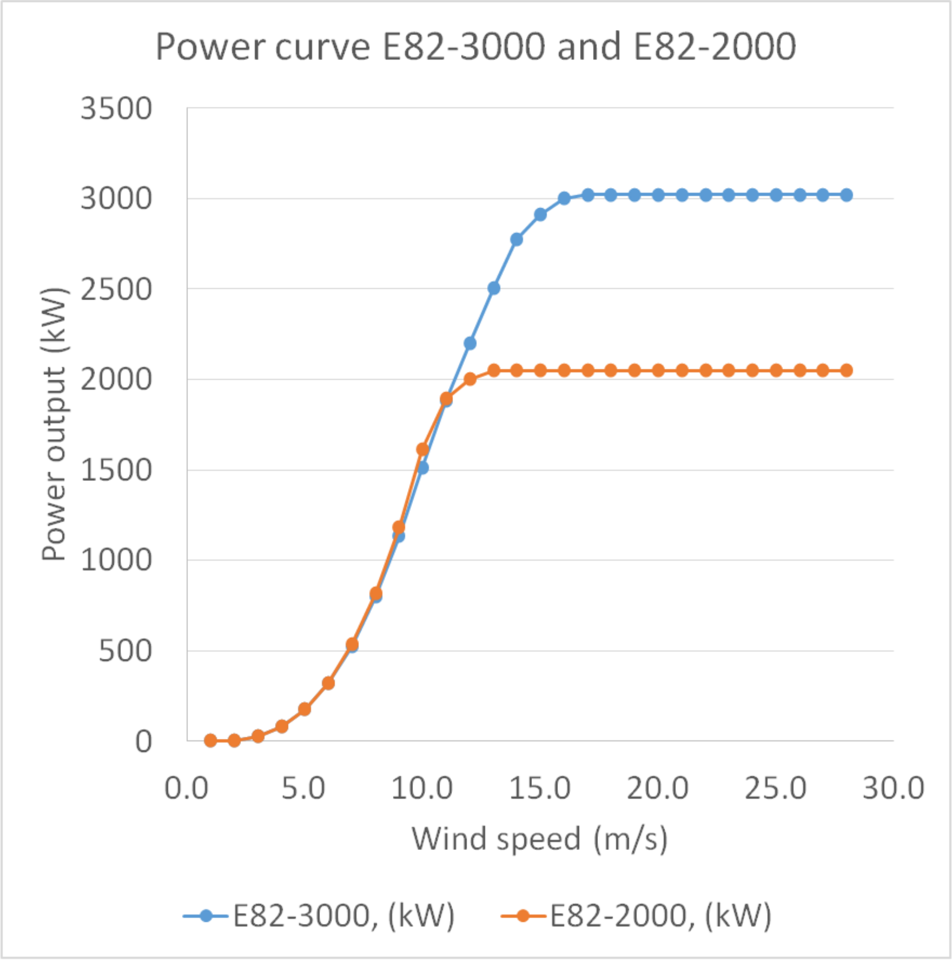
- Weibull distribution: shape factor k=1,25 and A= 8 m/s



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



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



Source: Enercon product information 2014

Worked example

5. ESTIMATING WIND CAPACITY AND YIELD AT A GIVEN SITE

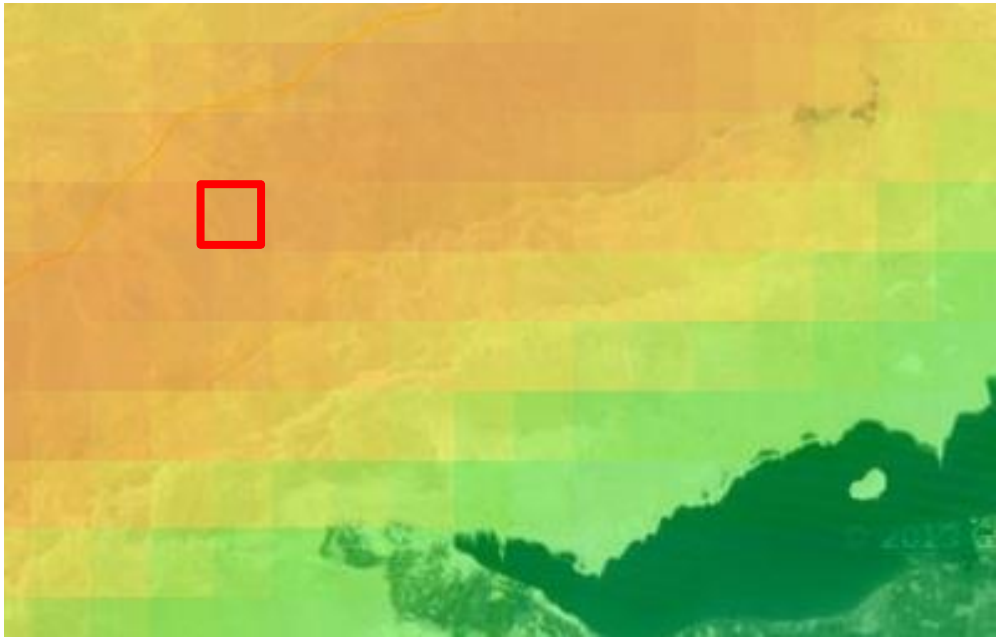
Wind energy yield estimation south-west of Cairo

- 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 km^2 at given location

Pen and paper exercise (start)

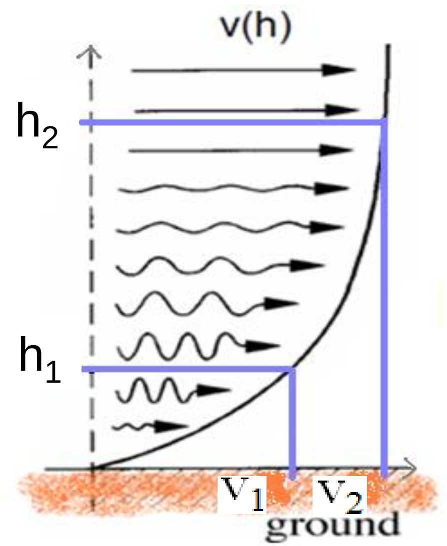
Retrieving average wind speed

- Average wind speed = **??? at 80 m height**



Extrapolation to hub height

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



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

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]

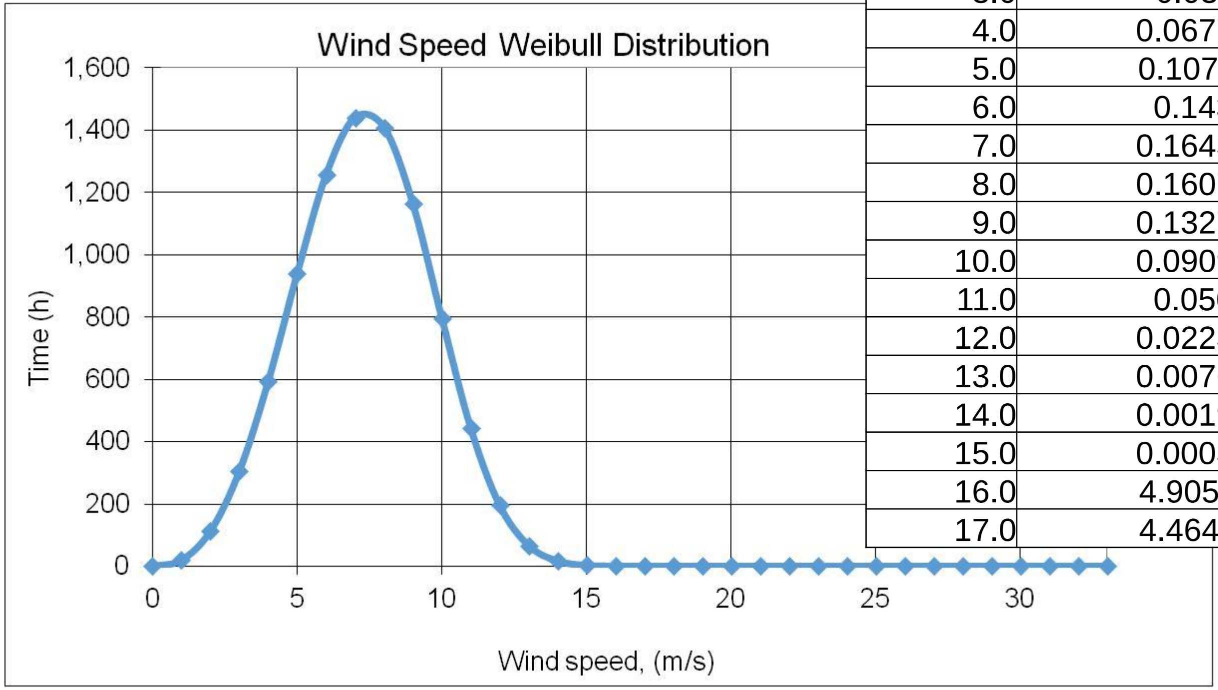
Estimating wind speed distribution

- Deriving Weibull distribution
  - Average wind speed: $v_2 = v_{avg} = 7.3$ m/s
  - Assumption (based on accessible data) → $k = 3.5$
  - Scaling factor: $v_{avg} = 0.9 * A$ → $A = v_{avg} / 0.9$

    $A = (v_{avg} / 0.9) = (7.3 \text{ m/s}) / 0.9 = 8.11$ m/s

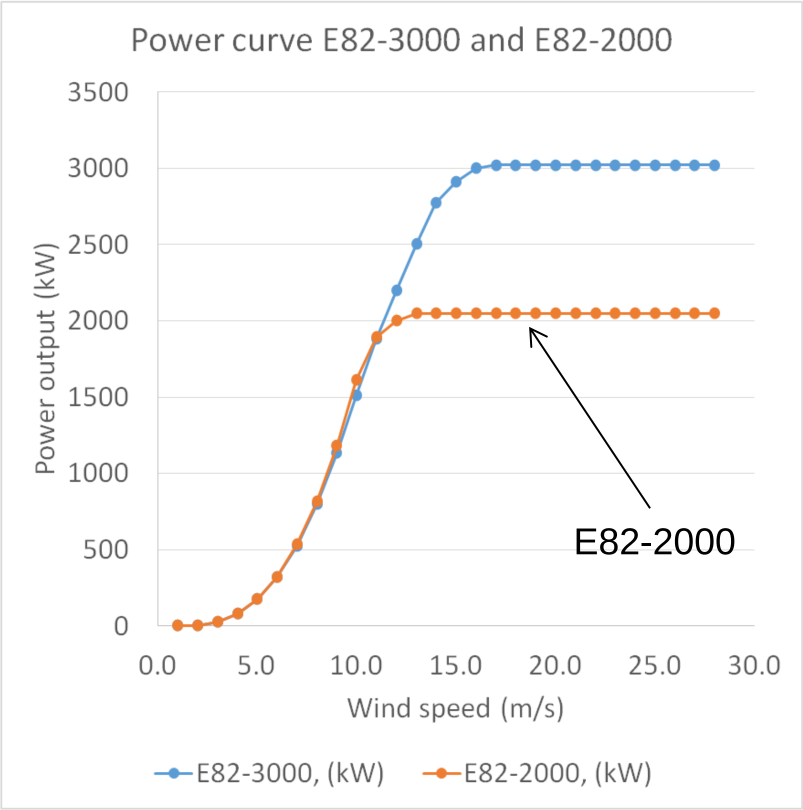
Resulting wind distribution

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



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

→ Pen and paper exercise

- Annual energy output of wind turbine at v_i = 6 m/s = **???**
- Annual energy output of wind turbine at v_i = 7 m/s = **???**

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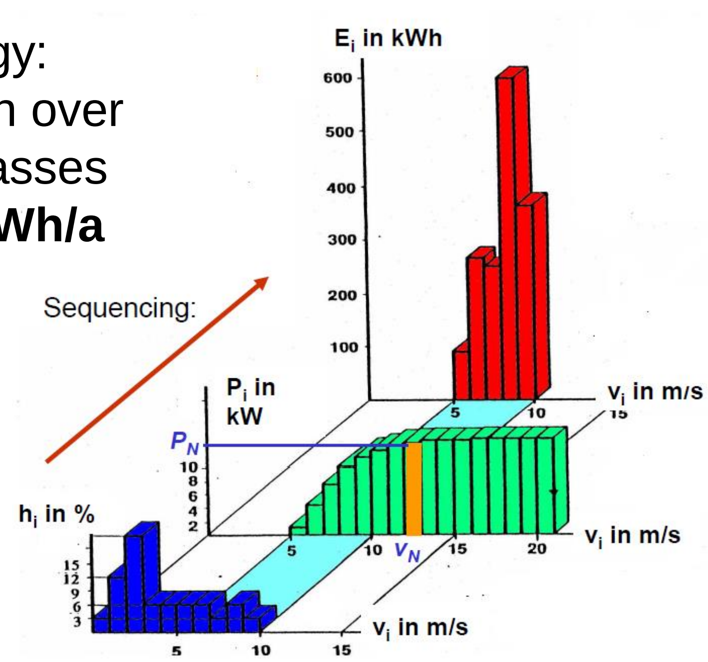
v_i (m/s)	**Output power of E82-2000, (kW)**
0.0	
1.0	0
2.0	3
3.0	25
4.0	82
5.0	174
6.0	321
7.0	532
8.0	815
9.0	1180
10.0	1612
11.0	1890
12.0	2000
13.0	2050
14.0	2050
15.0	2050
16.0	2050
17.0	2050

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

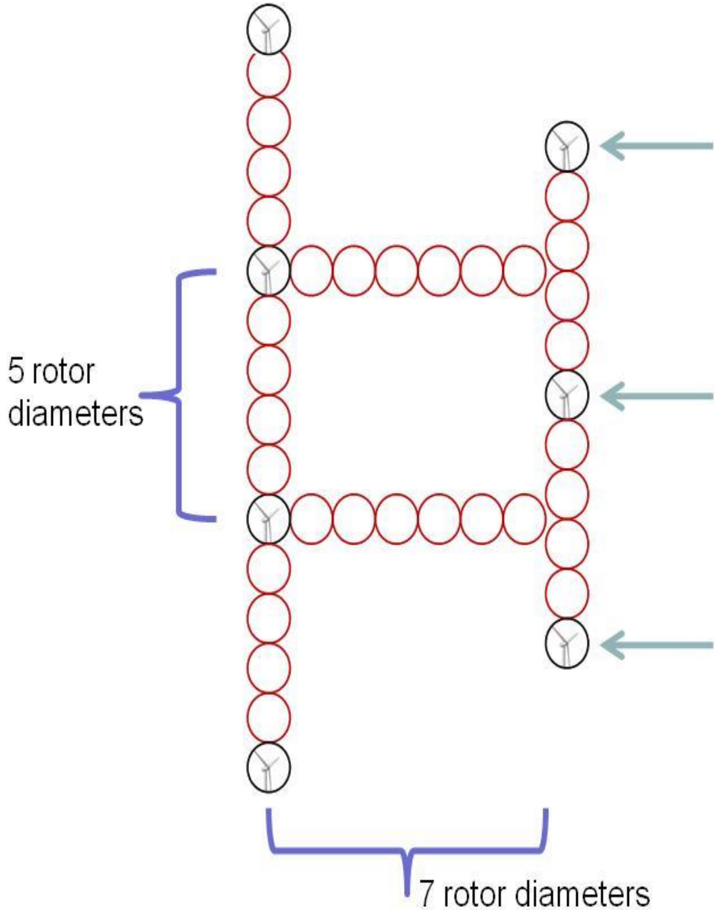
Example:
@ v=7.0 m/s:
1,439.5 h/a * 532 kW = 765,811 kWh/a

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



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**



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%**

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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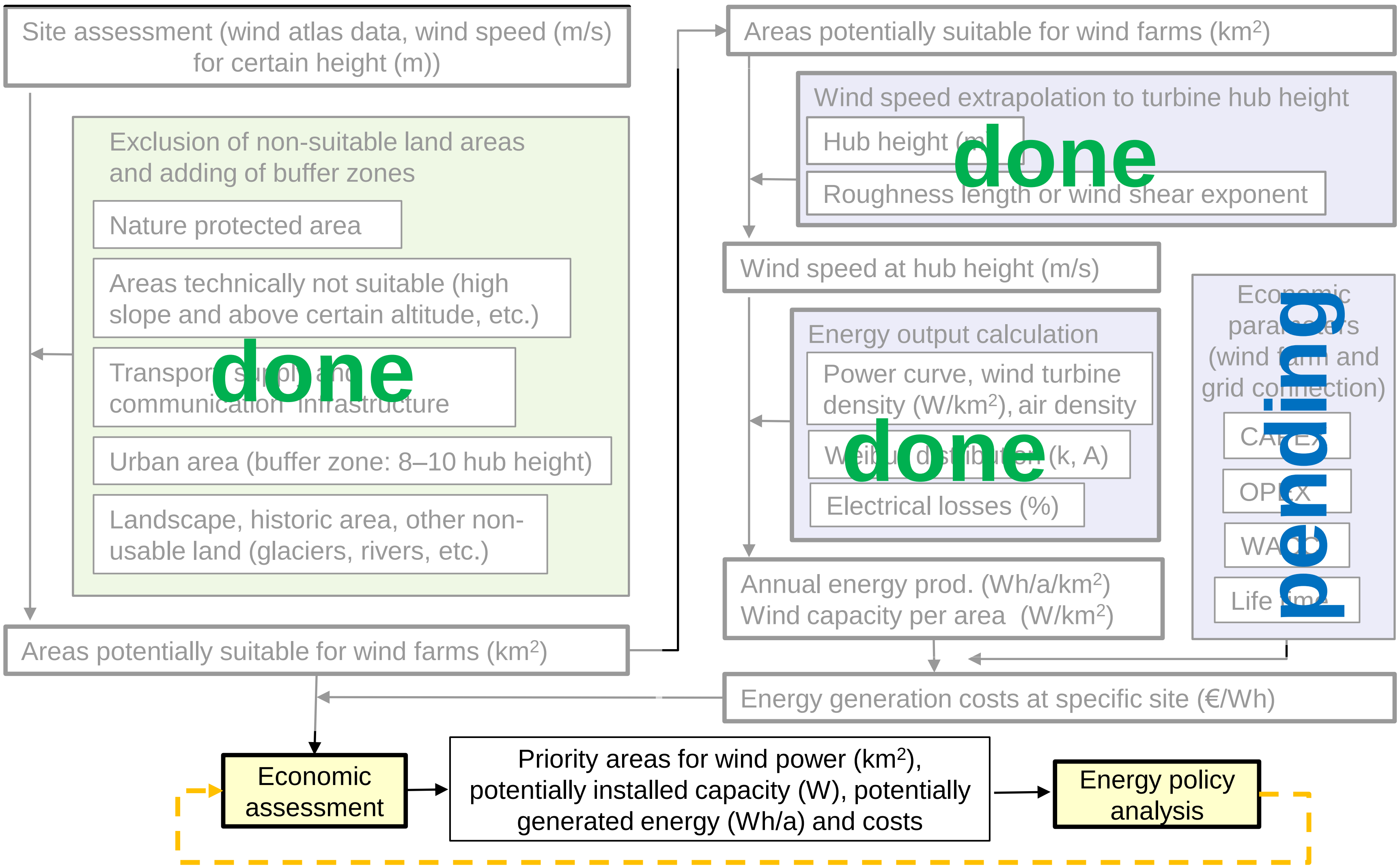

CAPEX = Capital expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (debt, equity)

Thank you very much for your attention!

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Solutions

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

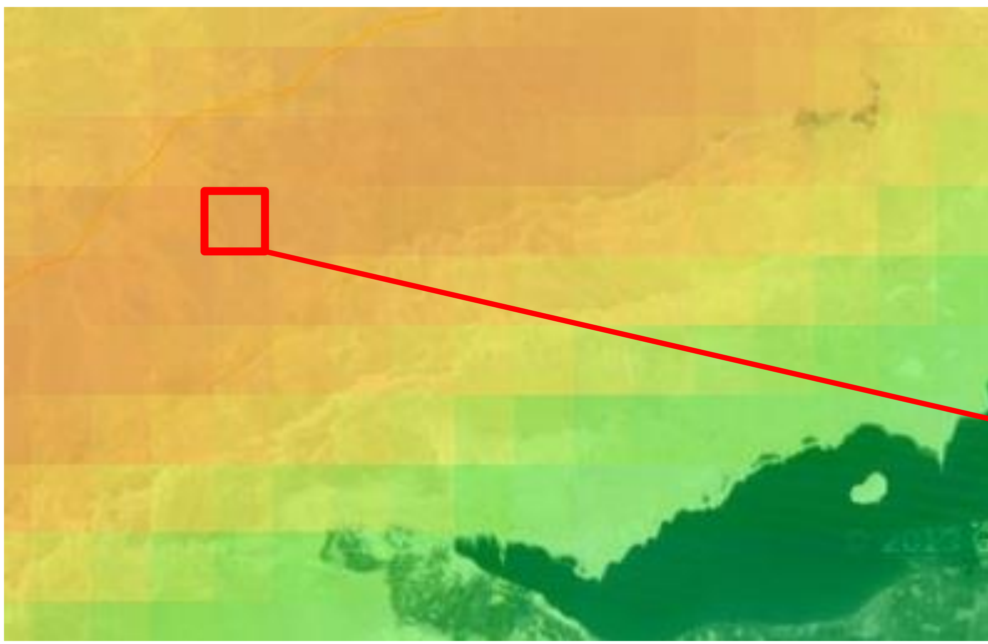
  Power = 0,5 * 1,225 kg/m^3 * **5**^3 m^3/s^3 * 25^2 m^2 * 3.1415 = 150 kW

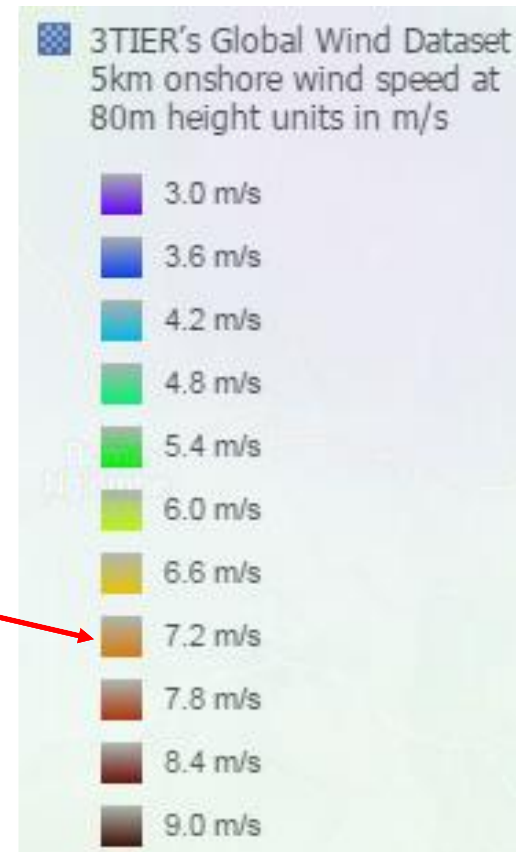
  Power = 0,5 * 1,225 kg/m^3 * **10**^3 m^3/s^3 * 25^2 m^2 * 3.1415 = 1202.6 kW

  Units:[kg/m^3 * ^3 m^3/s^3 * m^2 = Joule/s = W]

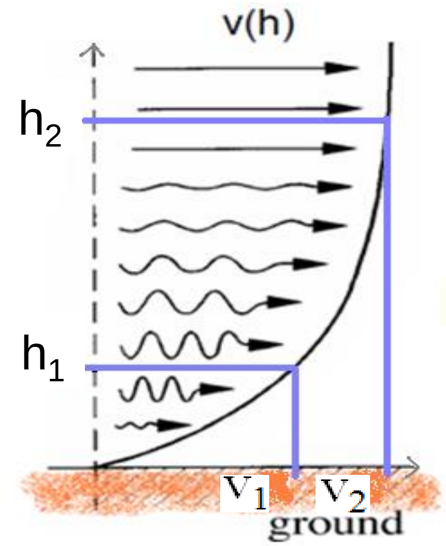
Retrieving average wind speed

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





Extrapolation to hub height



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

- **Result:** $\mathbf{v_2 = 7.3}$ **m/s**

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

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]