Wind Resource Assessment Training

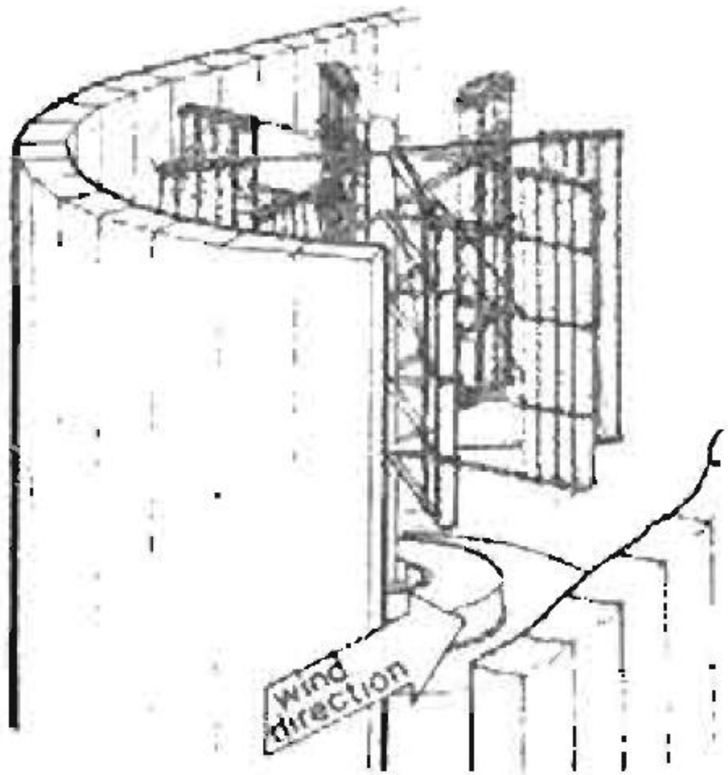
Dr. Taha Ouarda

Deputy Director, UAE Research Center for Renewable Energy Mapping and Assessment,
Professor of Water and Environmental Engineering

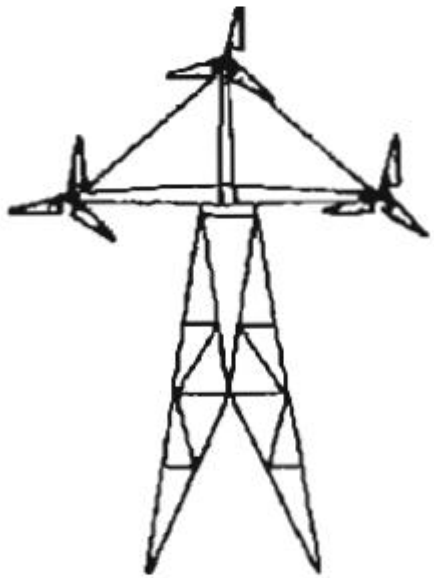
Abu Dhabi, October, 2013

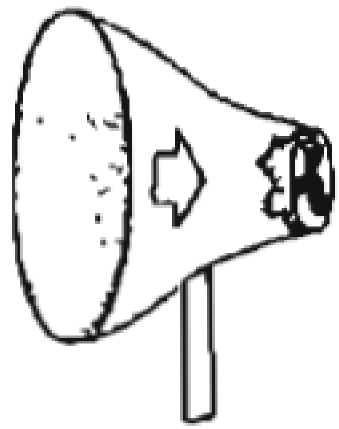
Brief history

Early Persian windmill (Gipe, 1995)



Various concepts for horizontal axis turbines (Eldridge, 1980)

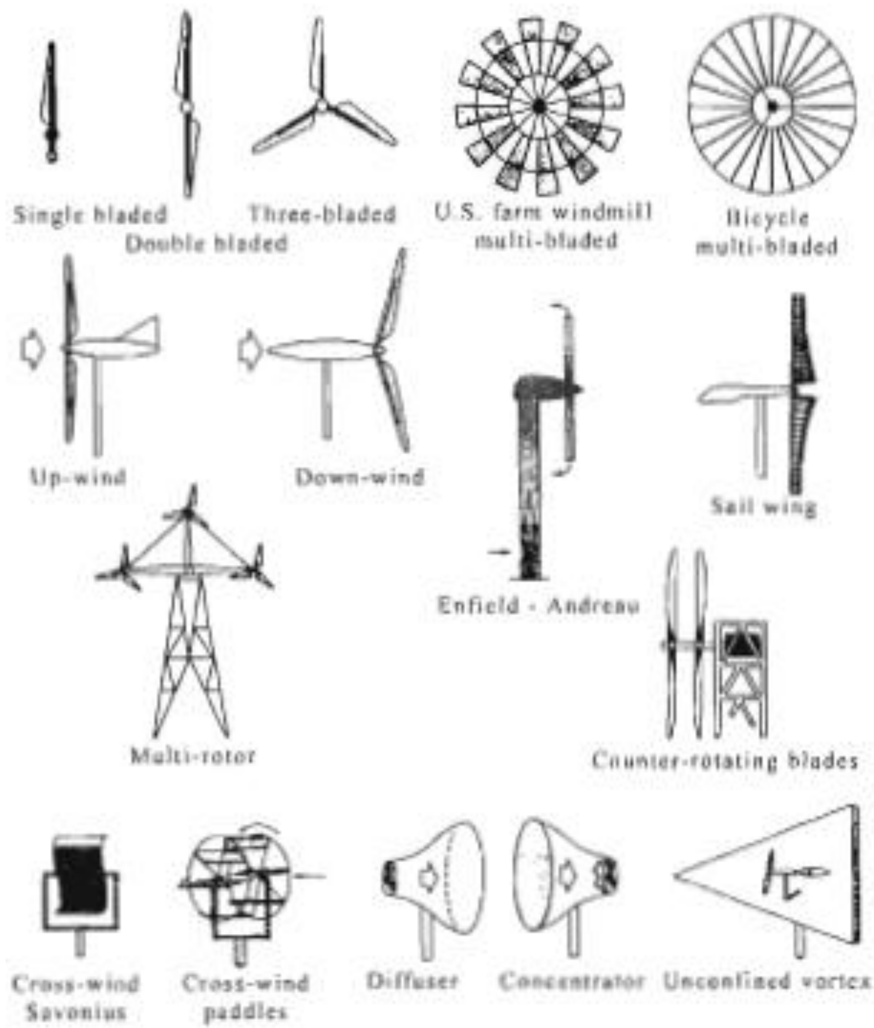




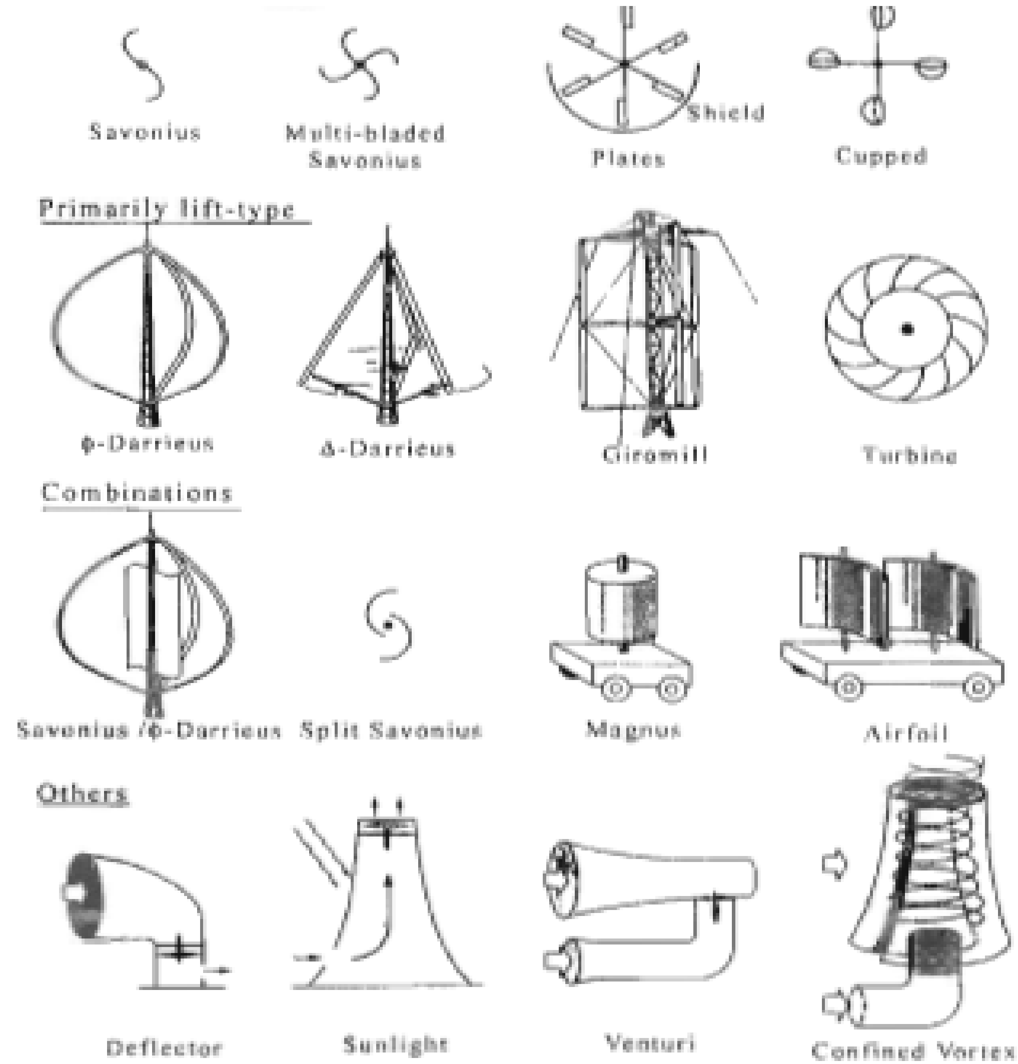
Overview

Configuration/Types:

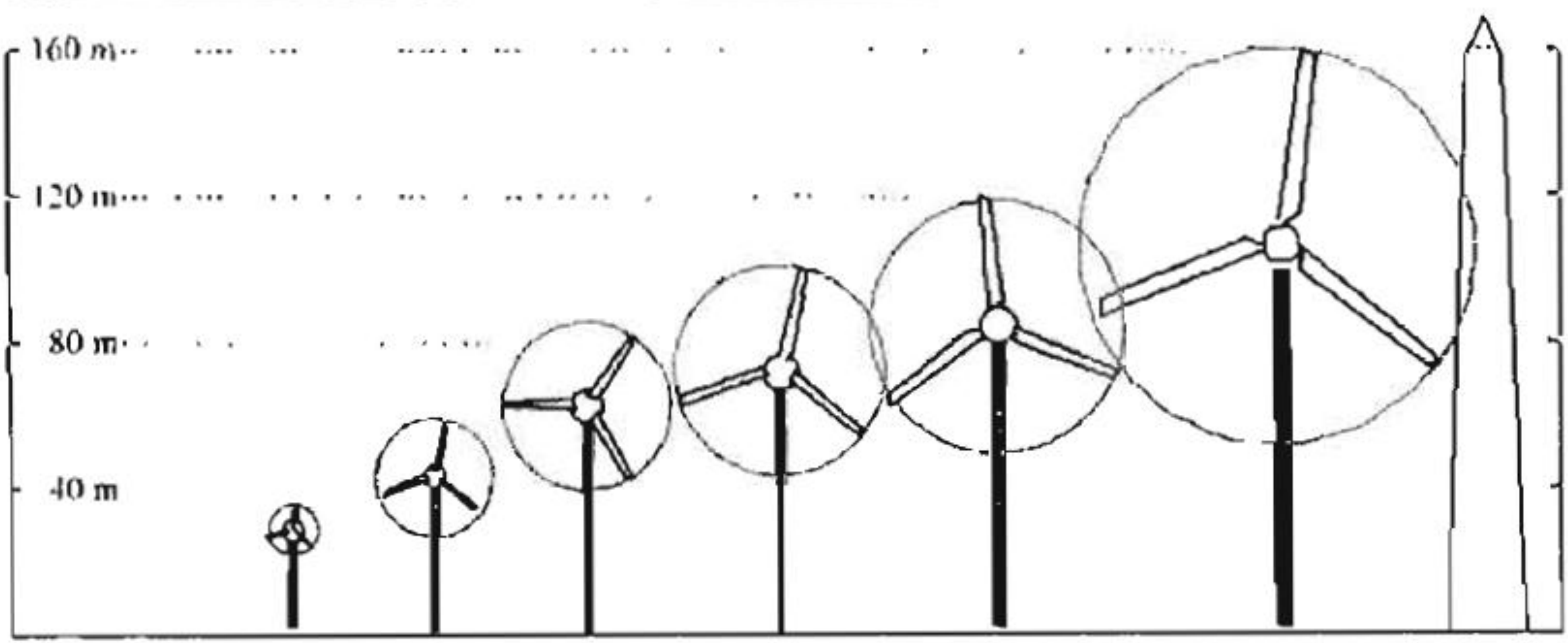
- Horizontal axis turbine



- Vertical axis turbine



Representative size, height, and diameter of wind turbines

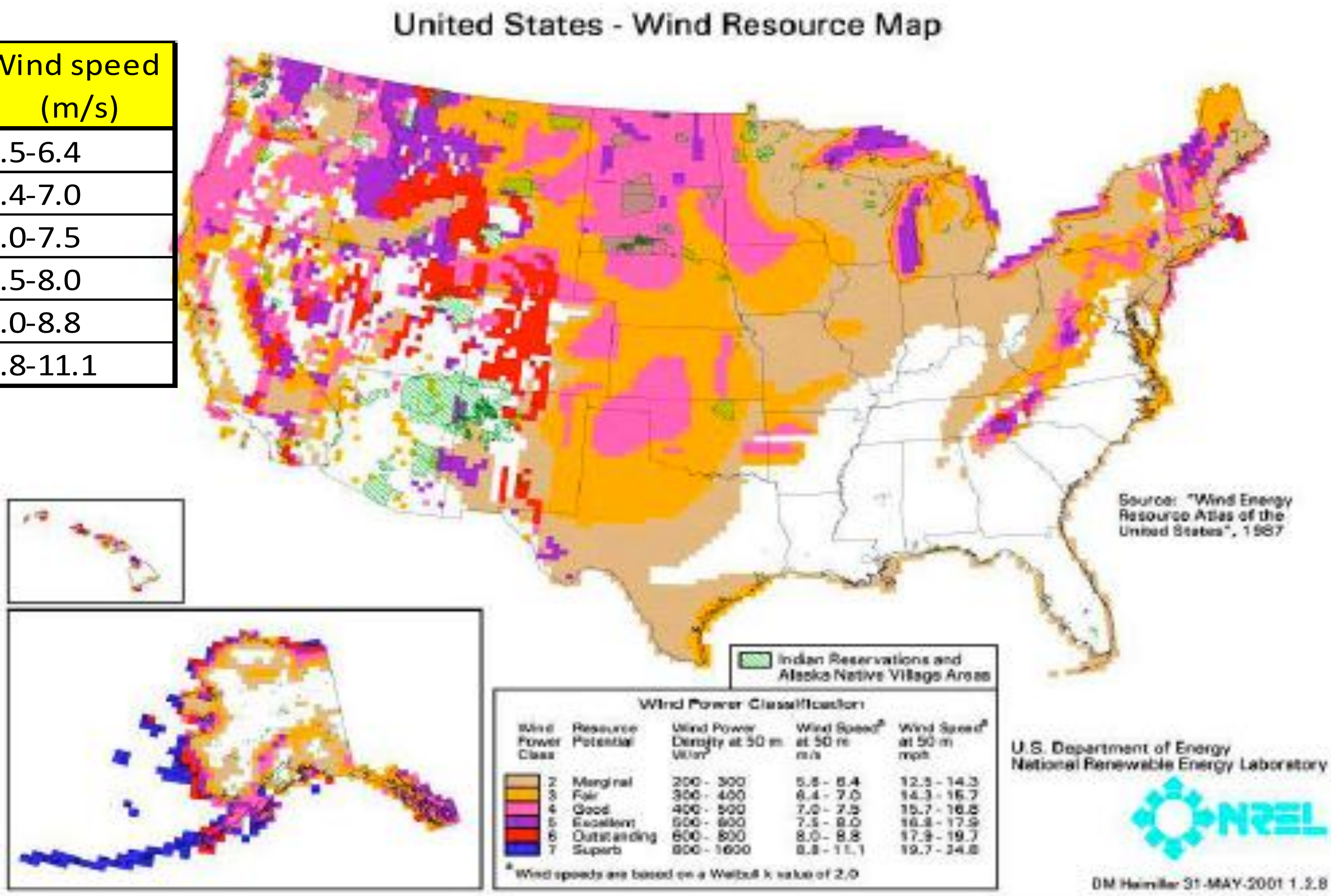


Rated capacity	50 kW	300 kW	750 kW	1000 kW	2000 kW	5000 kW	Washington Monument
Rotor diameter	15 m	34 m	48 m	60 m	72 m	112 m	
Tower height	25 m	40 m	60 m	70 m	80 m	100 m	170 m

US wind resources (2001):

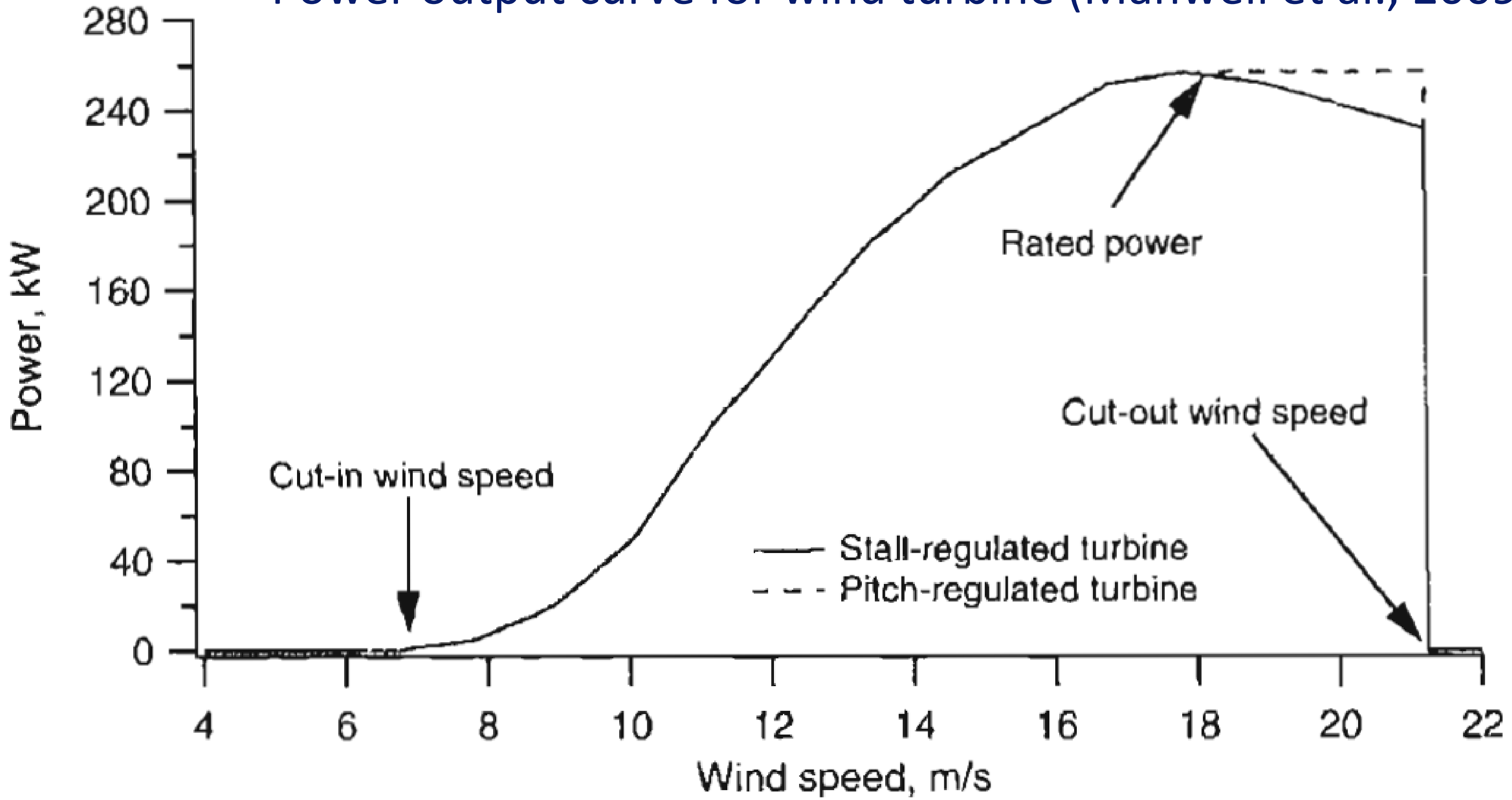
- Annual records Obtained at 50m height
- Wind Scale

Resources Potential	Power density (W/m^2)	Wind speed (m/s)
Marginal	200-300	5.5-6.4
Fair	300-400	6.4-7.0
Good	400-500	7.0-7.5
Excellent	500-600	7.5-8.0
Outstanding	600-800	8.0-8.8
Superb	800-1000	8.8-11.1



Typical wind turbine power curve

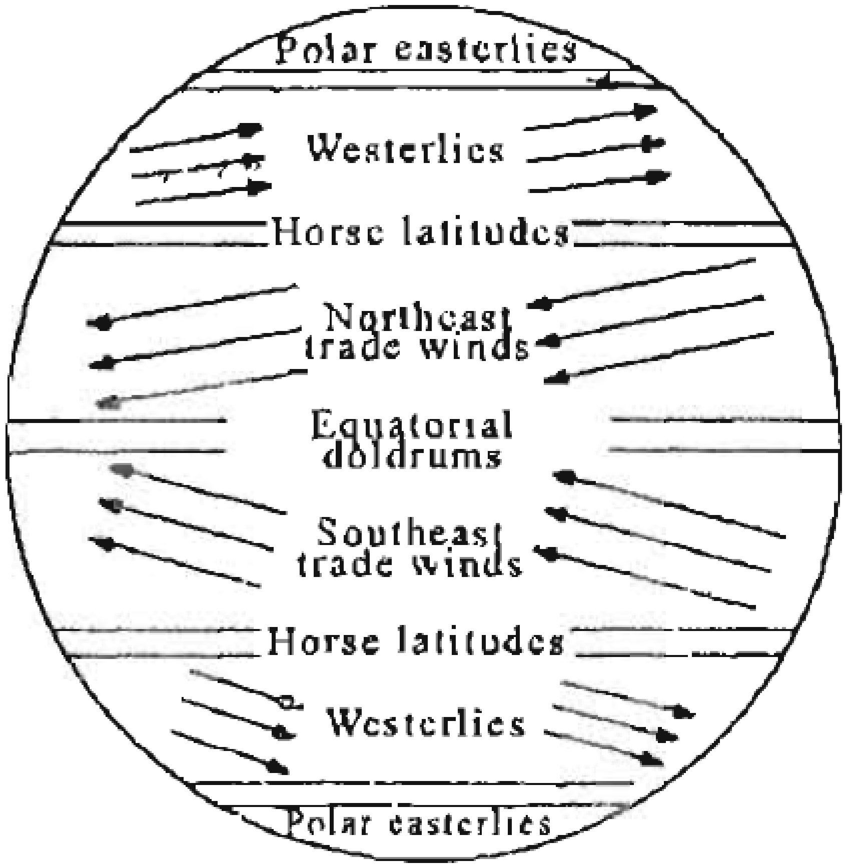
Power output curve for wind turbine (Manwell et al., 2009)



Origins of the wind resource

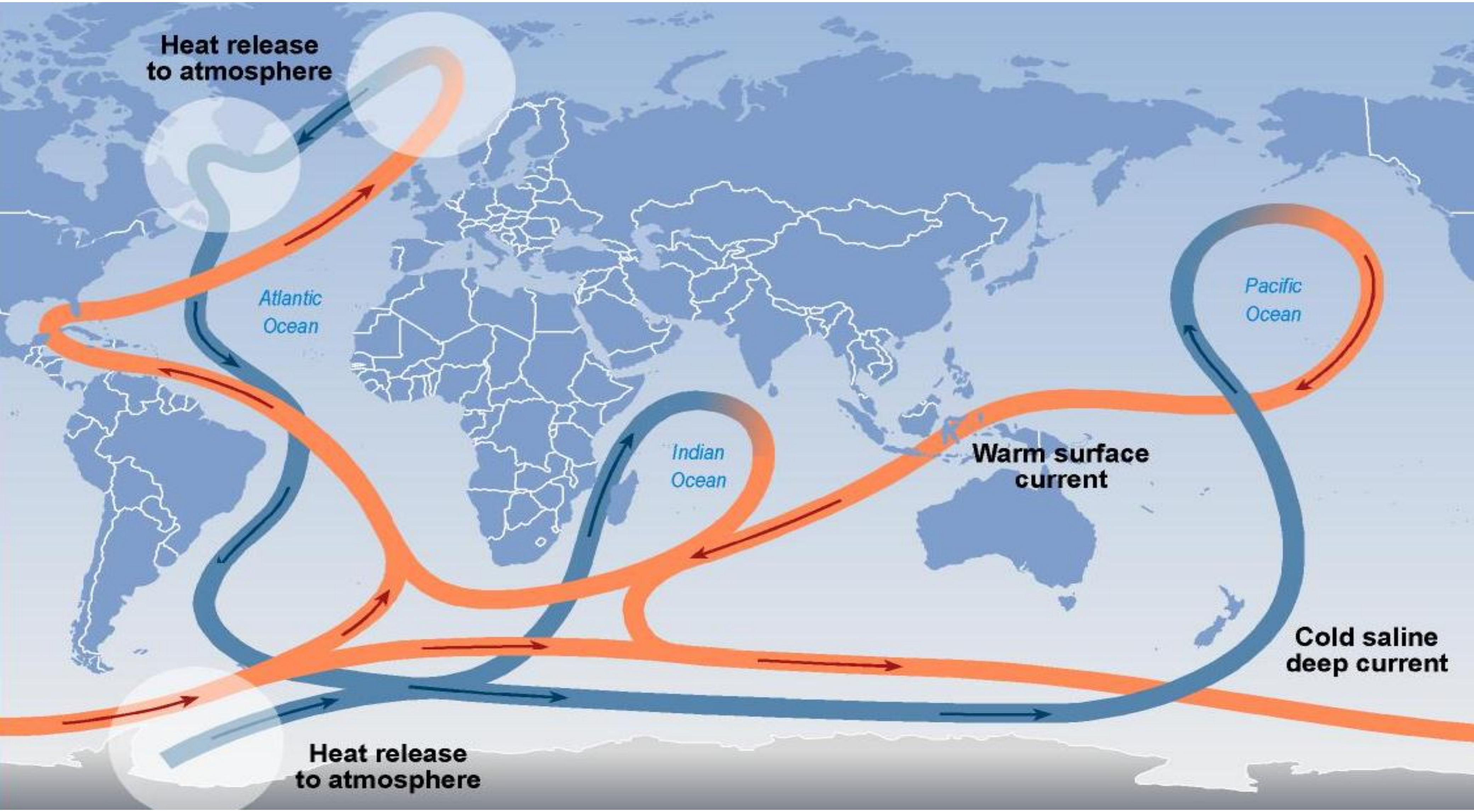
- Wind is mainly a response to **<u>pressure gradients</u>**: Global winds are caused by pressure differences across the earth's surface due to the uneven heating of the earth by solar radiation (absorption at equator vs. Poles).
- Simple model : air rises at the equator and sinks at the poles.
- Effect of the **<u>rotation of the earth</u>** (1670 km/hr at the equator).
- Influence of the seasonal variations in the spatial distribution of solar energy.
- gravitational forces, inertia of the air, friction with the earth's surface, the Coriolis force affect atmospheric winds.

Oversimplified model (smooth surface)



Surface winds of worldwide circulation pattern (Hiester and Pennell, 1981)

Thermohaline circulation of oceans



The big loop

Other atmospheric circulation patterns

- The earth's surface varies considerably: oceans, land masses.
- These different surfaces affect the flow of air due to variations in pressure fields, in the absorption of solar radiation, and the amount of moisture available.
- The oceans act as large energy sinks. Therefore ocean circulation affects the movement of air.
- In addition, local heating or cooling may cause persistent local winds to occur on a seasonal or daily basis. These include sea breezes and mountain winds.

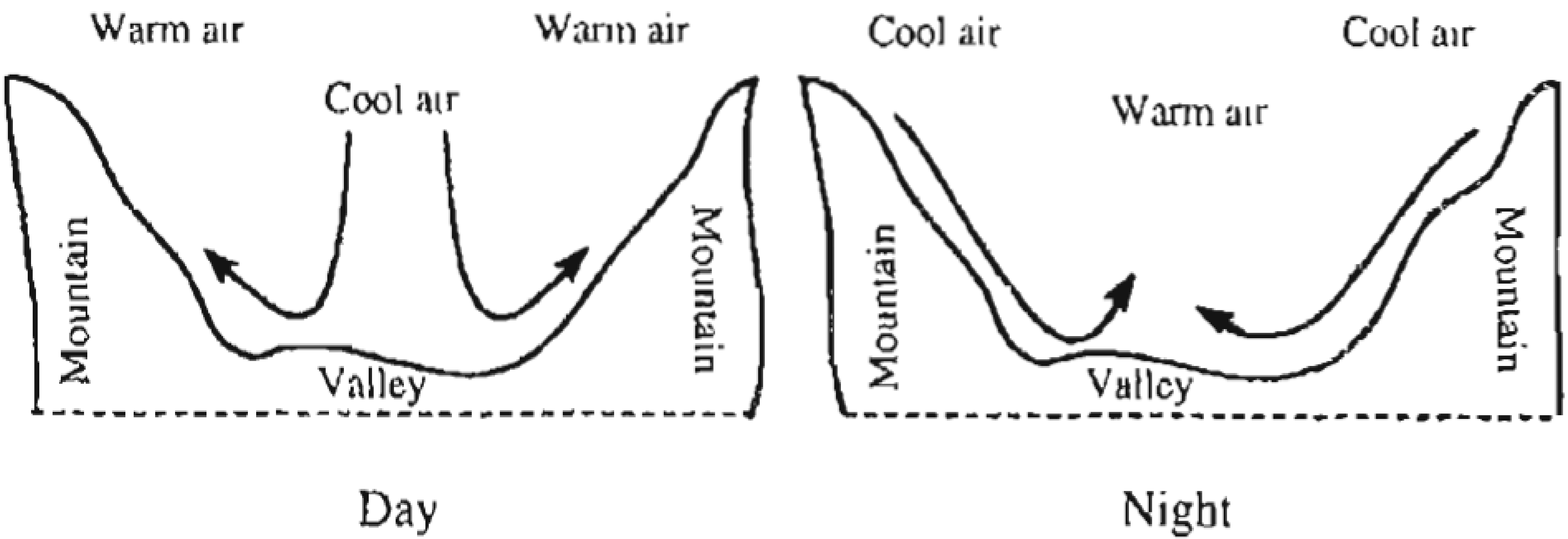
Secondary and tertiary circulation

- Smaller scale atmospheric circulation can be divided into secondary and tertiary circulation.
- Secondary circulation occurs if the centers of high or low pressure are caused by heating or cooling of the lower atmosphere: hurricanes, monsoon circulation, extratropical cyclones.
- Tertiary circulations are small-scale local circulations characterized by local winds: land and sea breezes, valley and montain winds, thunderstorms, tornadoes.
- An understanding of these wind patterns and other local effects is important for the evaluation of potential wind energy sites

Example of tertiary circulation

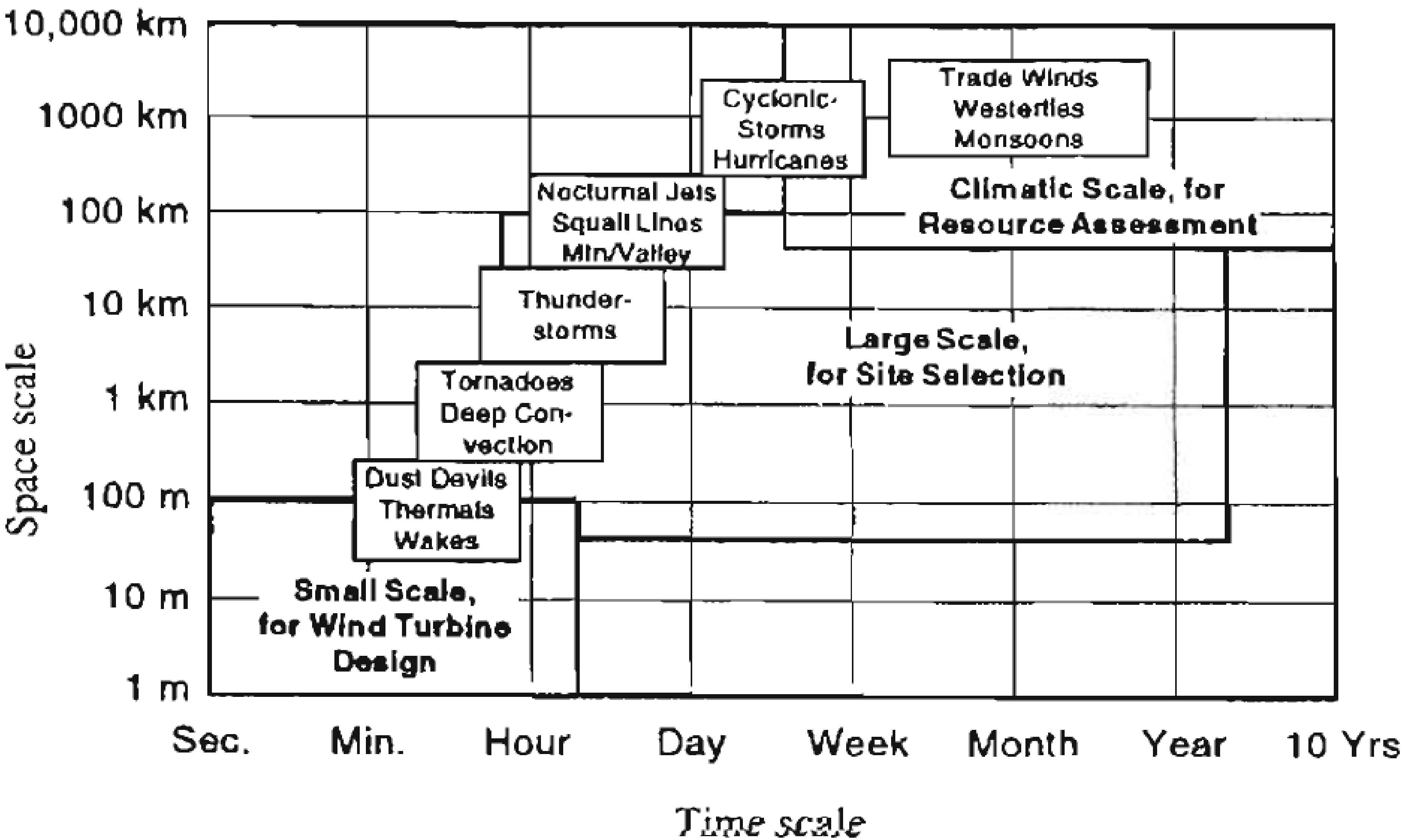
Day: the warmer air of the mountain slopes rises and replaces the heavier cool air above it.

Night: cold air drains down the slopes and stagnates in the valley floor.



Diurnal valley and mountain wind (Rohatgi and Nelson, 1994).

Time and space scales of atmospheric motion (Spera, 1994).

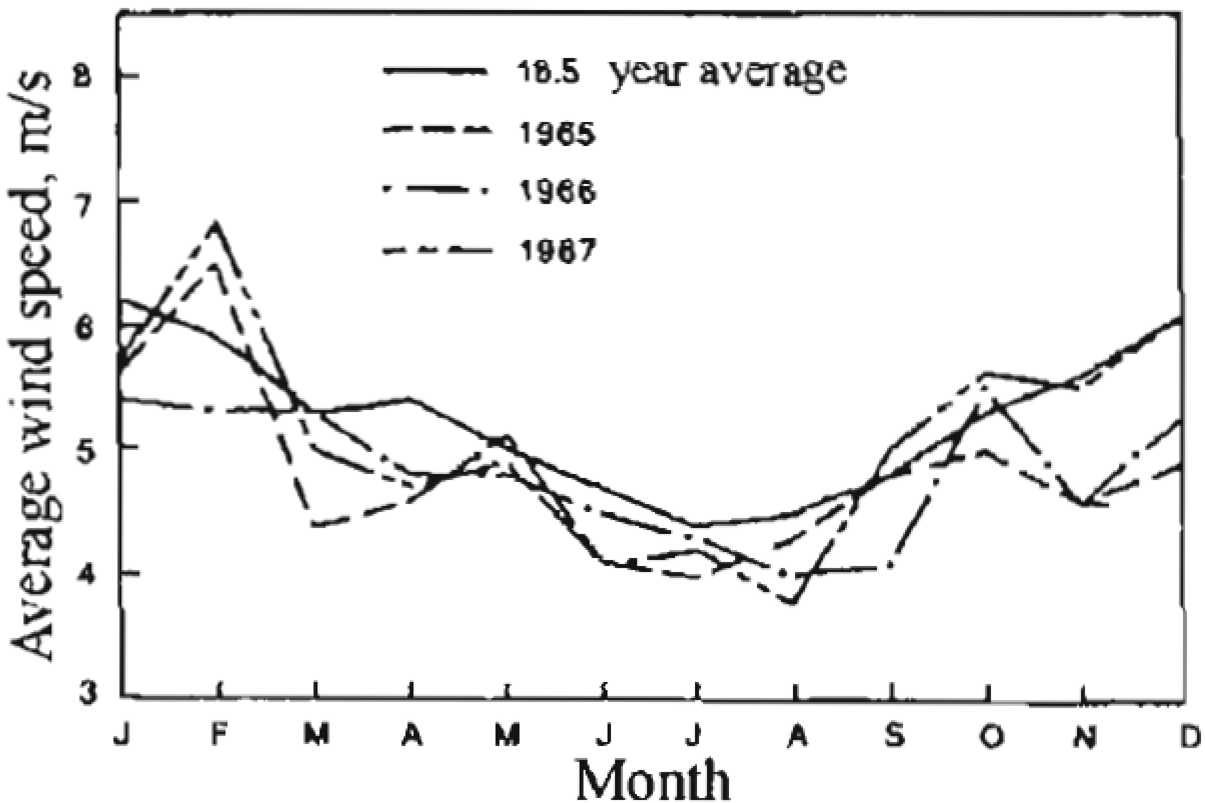


Variations in wind speed in time

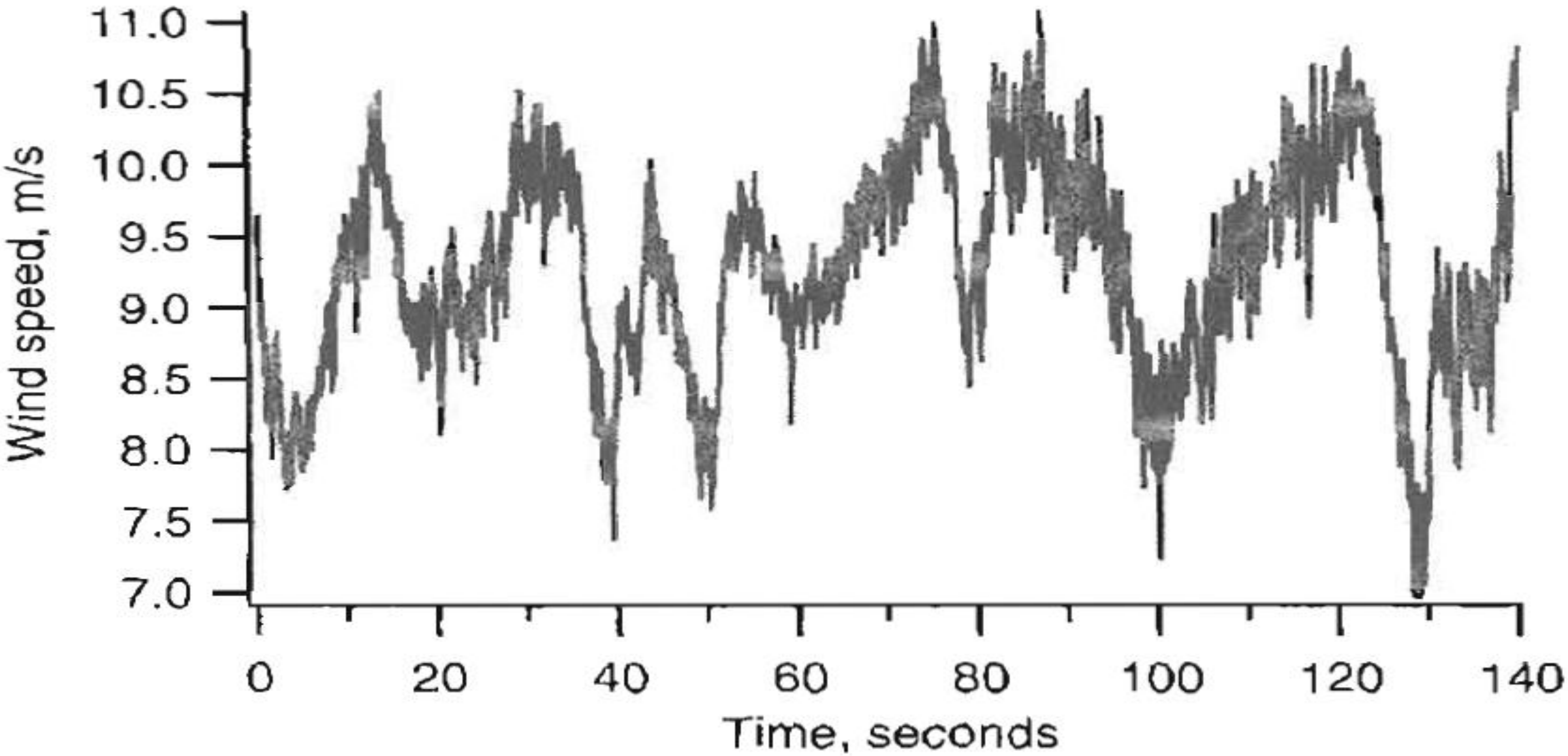
- Inter-annual variations in wind speed have a large effect on long-term wind turbine production.
- It takes 30 years of data to determine long-term values of weather or climate
- It takes at least 5 years to arrive at a reliable average annual wind speed at a given location.
- Rule of thumb: 1 year of record is generally sufficient to predict long-term seasonal mean wind speeds within an accuracy of 10% with a confidence level of 90%.

Can a single year define the typical behaviour ?

Seasonal changes of monthly average wind speeds for Billings, Montana, USA (Hiester and Pennell, 1981)



Short time wind speed variations



Typical plot of wind speed vs. time for a short period

Short time wind speed variations

- These are variations over time intervals of ten minutes or less (sampling rate of about 1second).
- These variations have a stochastic character and are considered to represent turbulence.
- These turbulent fluctuations need to be quantified for wind energy applications.
- Turbulent fluctuations occur in all 3 directions: longitudinal (in the direction of the wind), lateral (perpendicular to the average wind) and vertical.
- These fluctuations are useful for turbine design considerations: maximum load, fatigue prediction, structural excitations, control, system operation, power quality, etc.).

Illustration of a discrete gust event

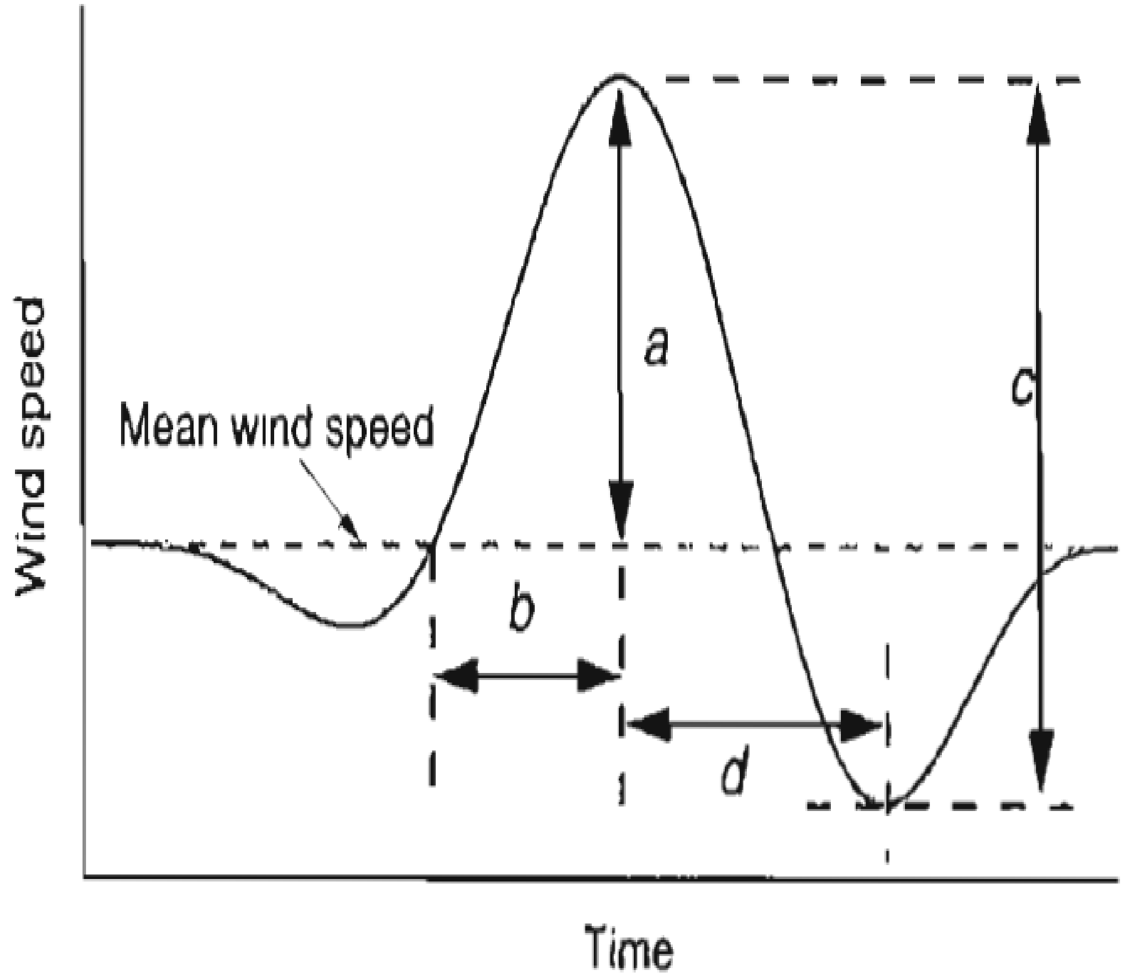
a: amplitude;

b: rise time;

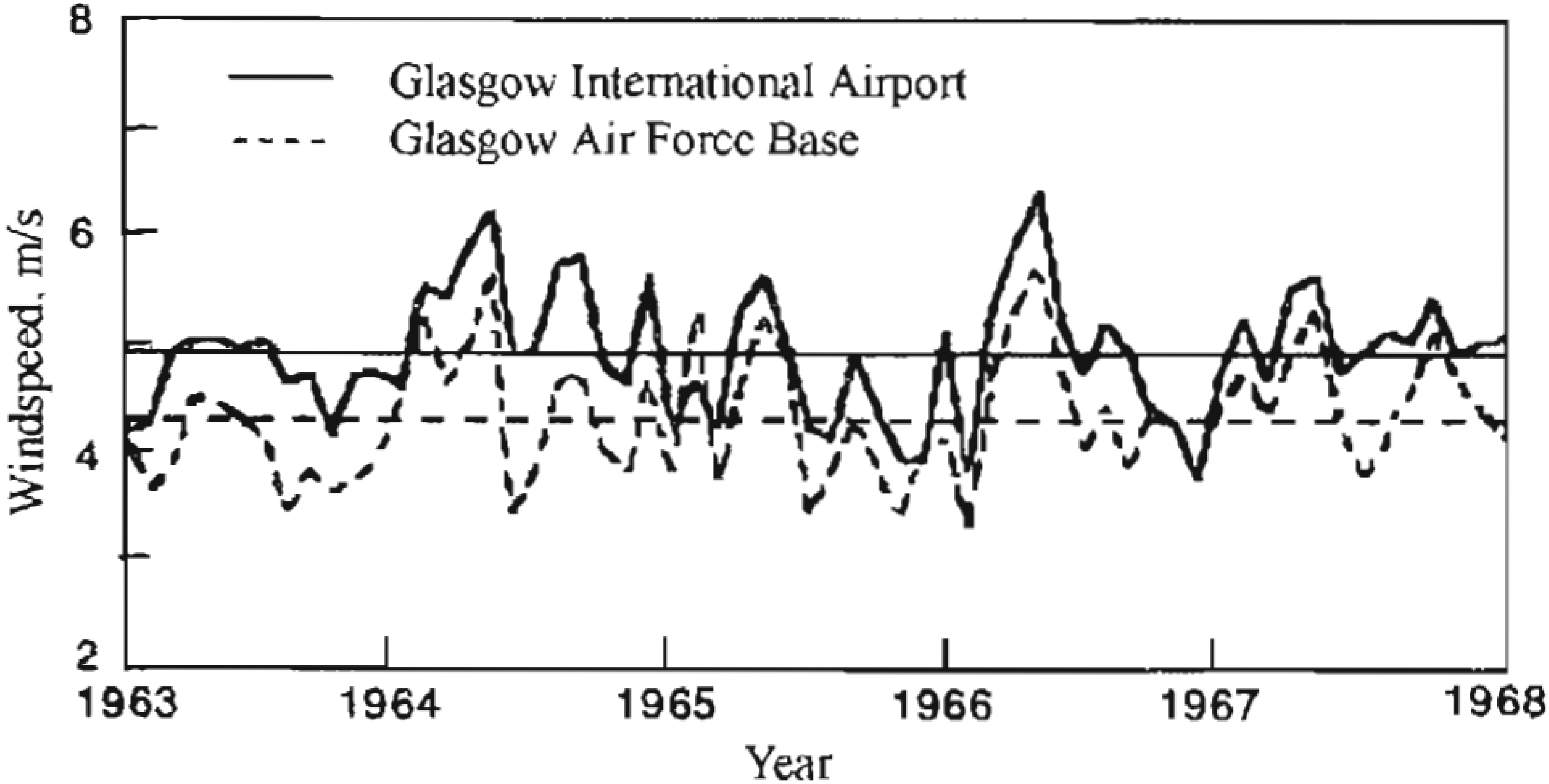
c: maximum gust variation;

d: lapse time

Wind turbine structural loads caused by gusts are affected by these four factors



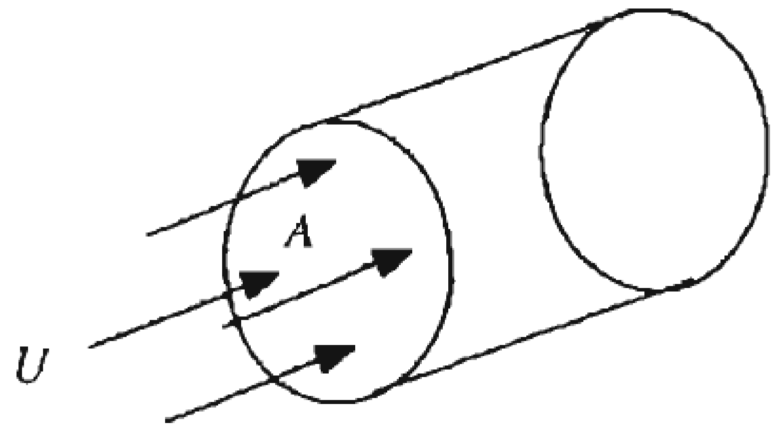
Variations due to location



Time series of monthly wind speeds for Glasgow, Montana International Airport and Air Force Base (AFB). The two sites are 21 km apart (Hiester and Pennell, 1981)

Available wind power

$$\frac{dm}{dt} = \rho AU$$



Flow of air through a rotor disk; A, area; U, wind velocity

Available wind power

The kinetic energy per unit time, or power, of the flow is given by:

$$P = \frac{1}{2}\frac{dm}{dt}U^2 = \frac{1}{2}\rho A U^3$$

The wind power per unit area, P/A or wind power density is:

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

Importance of wind velocity

Power per unit area available from steady wind (air density = 1.225 kg/m^3)

Wind Speed (m/s)	Power/Area (W/m^2)
0	0
5	80
10	610
15	2,070
20	4,900
25	9,560
30	16,550

Wind power classes

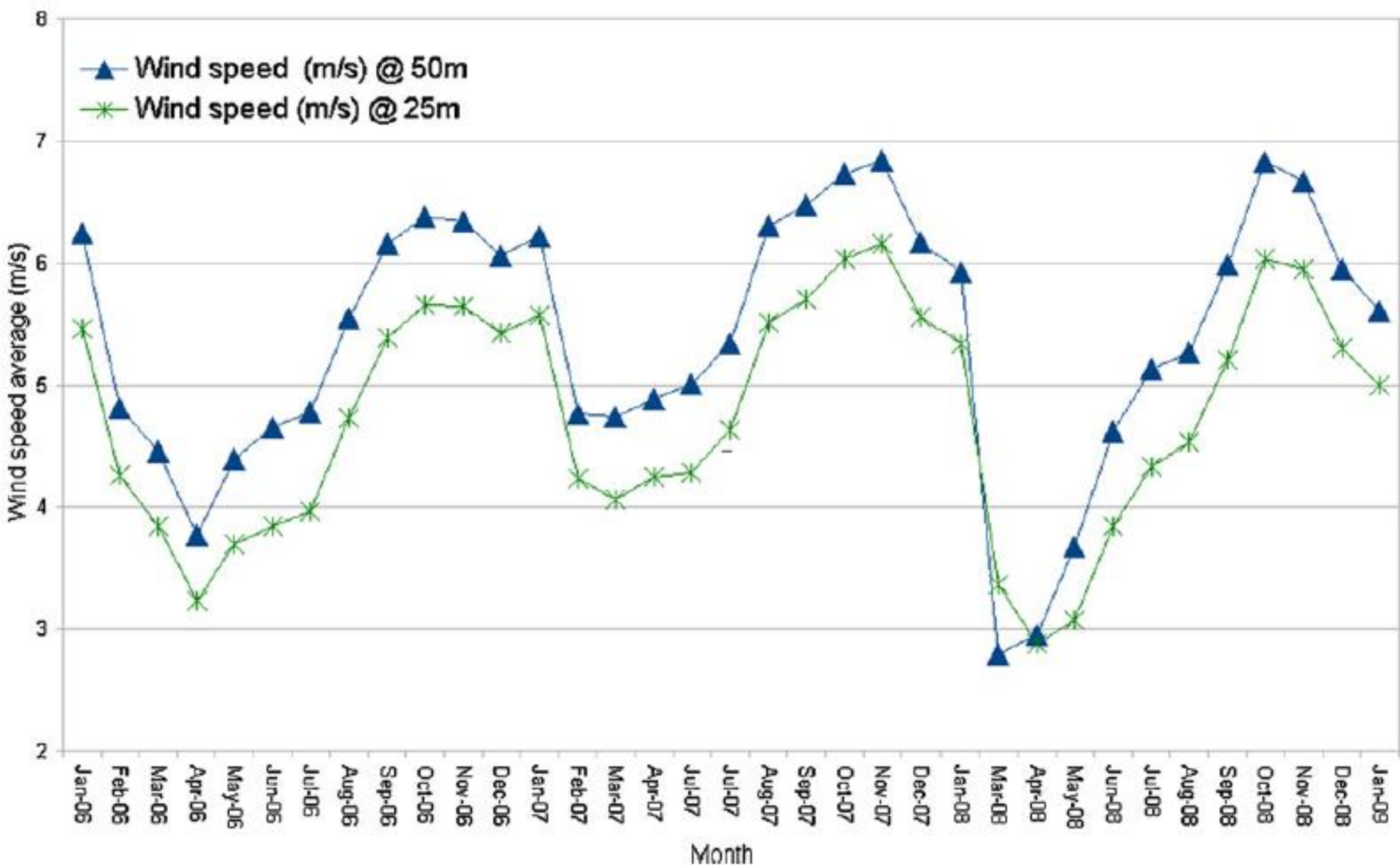
- Class 4 or greater are suitable for most wind turbine applications.
- Class 3 areas are suitable for wind energy development using tall (e.g., 50m hub height) turbines
- Class 2 areas should not be ruled out.
- The technology keeps improving

Classes of Wind Power Density

	30 m (98 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Wind Speed m/s (mph)	Wind Power Density (W/m^2)	Wind Speed m/s (mph)
1	≤160	≤5.1 (11.4)	≤200	≤5.6 (12.5)
2	≤240	≤5.9 (13.2)	≤300	≤6.4 (14.3)
3	≤320	≤6.5 (14.6)	≤400	≤7.0 (15.7)
4	≤400	≤7.0 (15.7)	≤500	≤7.5 (16.8)
5	≤480	≤7.4 (16.6)	≤600	≤8.0 (17.9)
6	≤640	≤8.2 (18.3)	≤800	≤8.8 (19.7)
7	≤1600	≤11.0 (24.7)	≤2000	≤11.9 (26.6)

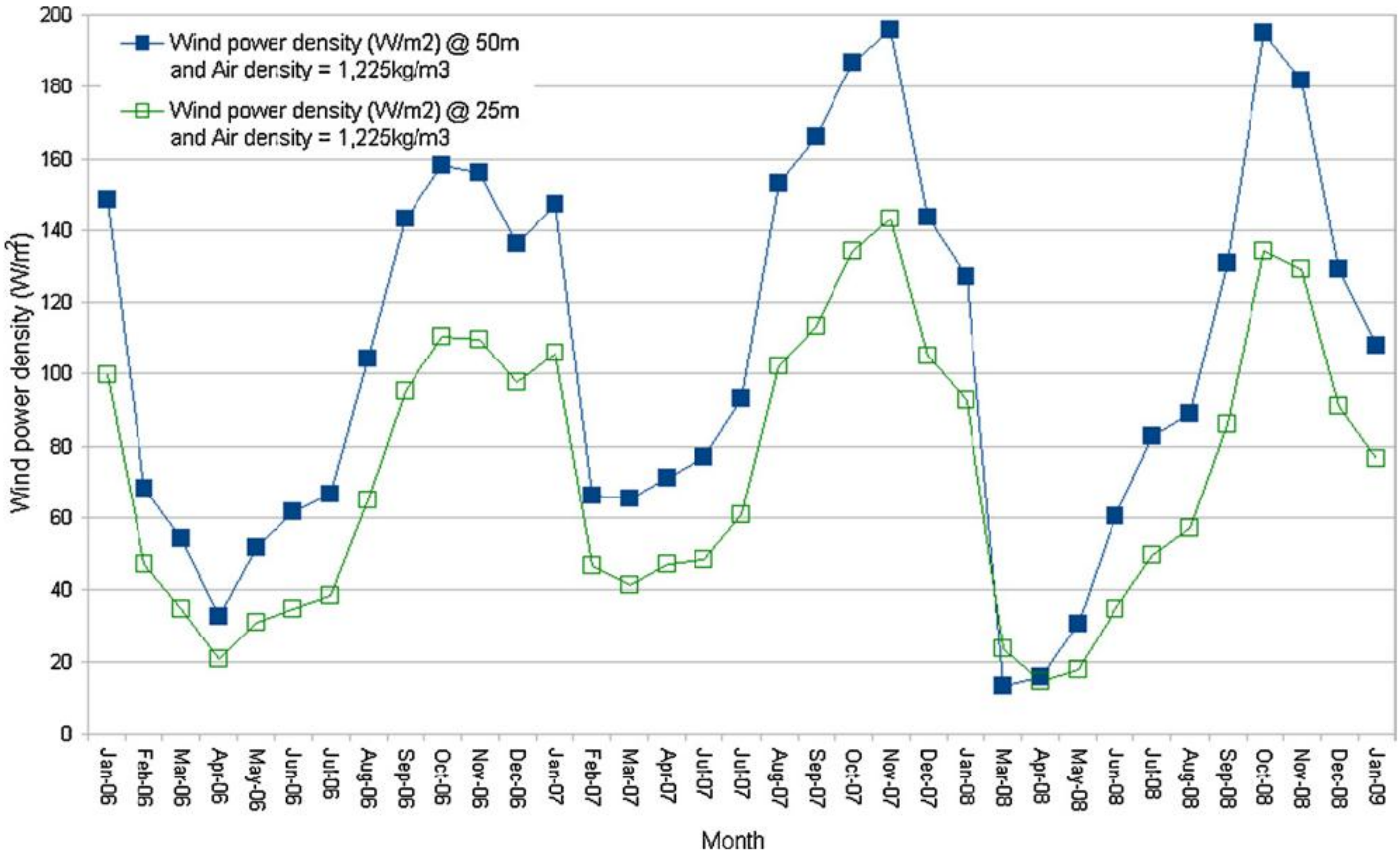
Wind shear

Monthly wind speed average at 25 and 50 m from SJC meteorological station.



Wind shear

Monthly wind power average at 25 and 50 m from SJC meteorological station.



Vertical wind speed power law profile

$$v_2 = v_1 \times \left[\frac{z_2}{z_1} \right]^{\alpha}$$

where

v_2 = the unknown speed at height z_2
v_1 = the known wind speed at the measurement height z_1
α = the wind shear exponent.

Vertical wind speed power law profile

$$\alpha = \frac{Log_{10}\left[\frac{v_2}{v_1}\right]}{Log_{10}\left[\frac{z_2}{z_1}\right]}$$

where

v_2 = the wind speed at height z_2; and
v_1 = the wind speed at height z_1.

Vertical wind speed power law profile

The wind shear exponent (or power law exponent) varies with such parameters as elevation, time of day, season, nature of the terrain, wind speed, temperature and various thermal and mechanical mixing parameters.

Wind turbulence

Wind turbulence is the rapid disturbances or irregularities in wind speed, direction and vertical component. High turbulence levels may decrease power output and cause extreme loading on wind turbine components. The most common indicator of turbulence for siting purposes is the standard deviation of wind speed. Normalizing this value with the mean wind speed gives the turbulence intensity (L, 0.1, M. 0.25, H. 0.5)

$$TI = \frac{\sigma}{V}$$

where

σ = the standard deviation of wind speed; and
V = the mean wind speed.

Effect of terrain on wind characteristics

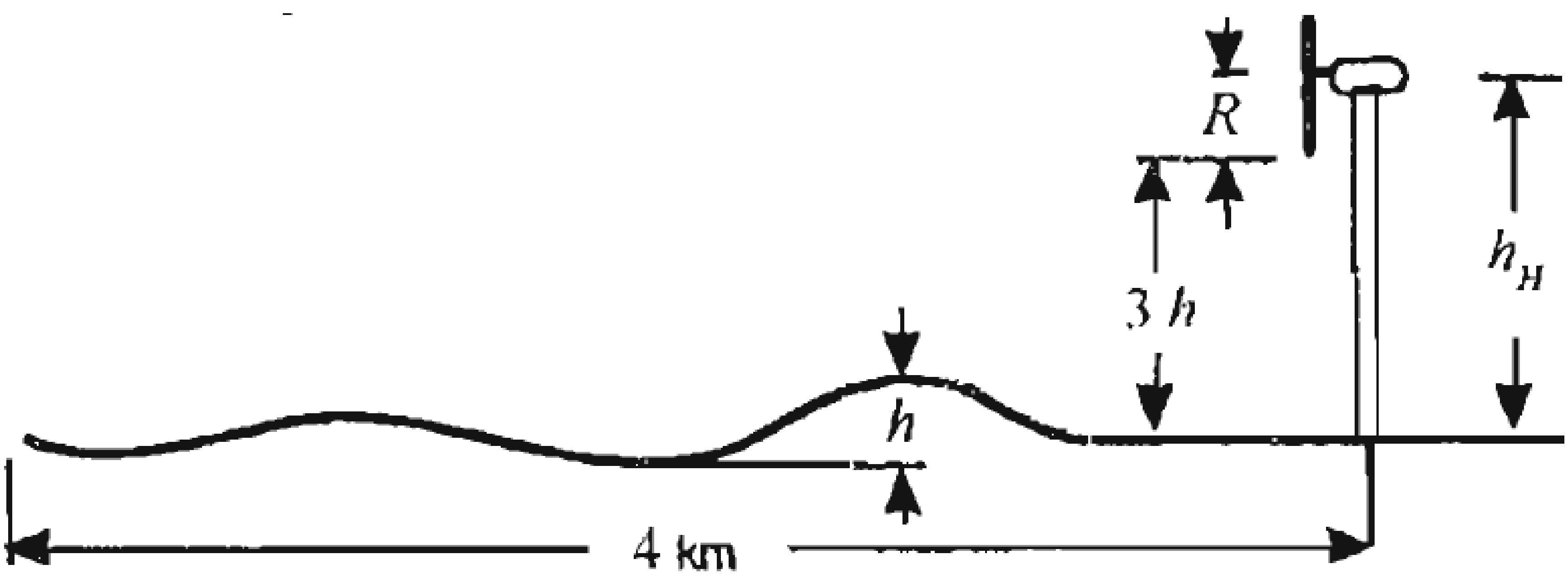
- The terrain influences wind velocity, wind acceleratin and wind shear.
- In the logarithmic law for modeling the vertical wind speed profile, the surface roughness length plays an important role.
- The most basic classification of terrain divides it into flat and non-flat terrain.
- Non-flat terrrain has large-scale elevations or depressions such as hills, valleys, and canyons.

Surface roughness

Values of surface roughness length for various types of terrain

Terrain Description	z_0 (mm)
Very smooth, ice or mud	0.01
Calm open sea	0.20
Blown sea	0.50
Snow surface	3.00
Lawn grass	8.00
Rough pasture	10.00
Fallow field	30.00
Crops	50.00
Few trees	100.00
Many trees, hedges, few buildings	250.00
Forest and woodlands	500.00
Suburbs	1500.00
Centers of cities with tall buildings	3000.00

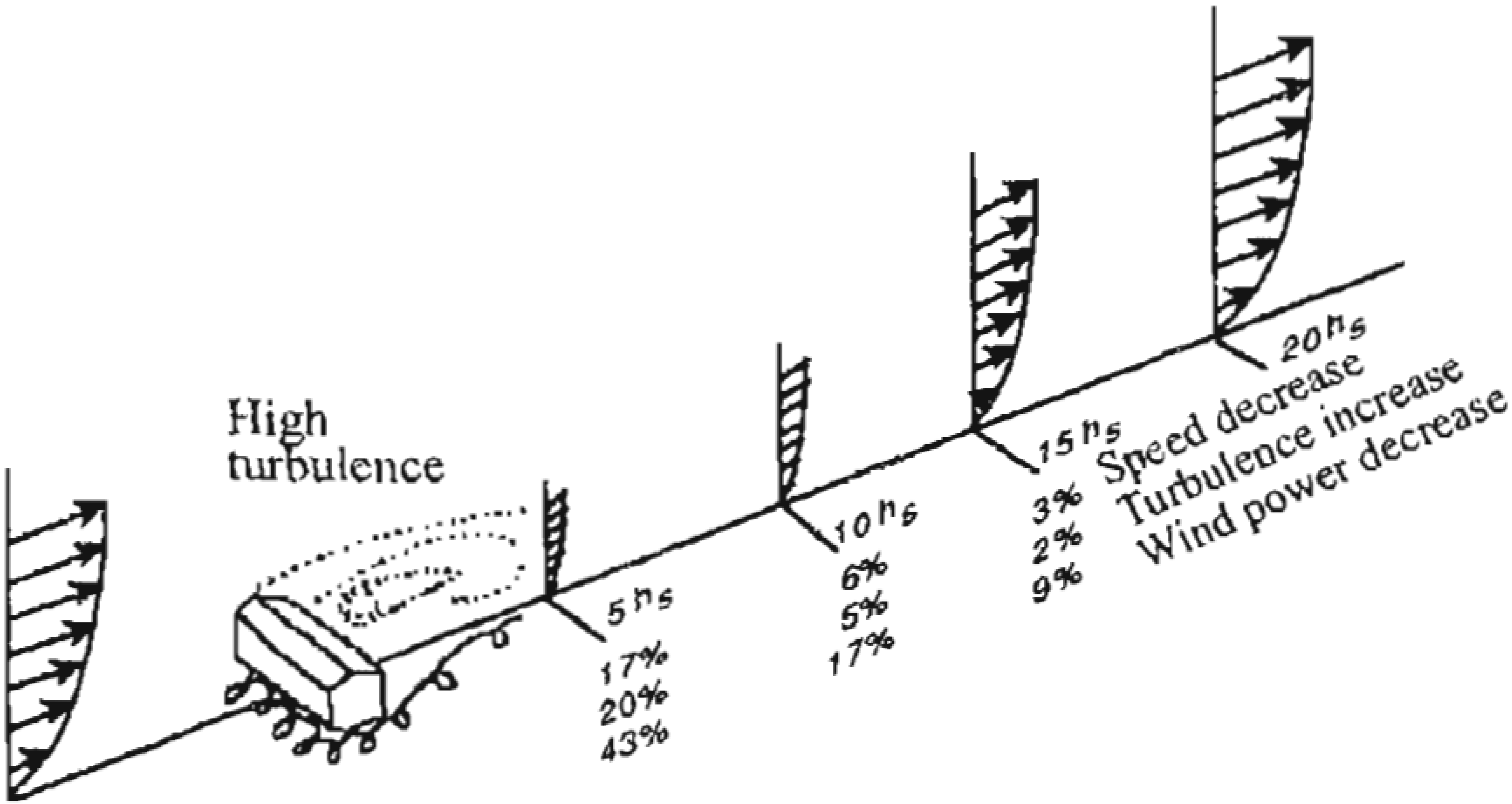
Flat terrain characterisation



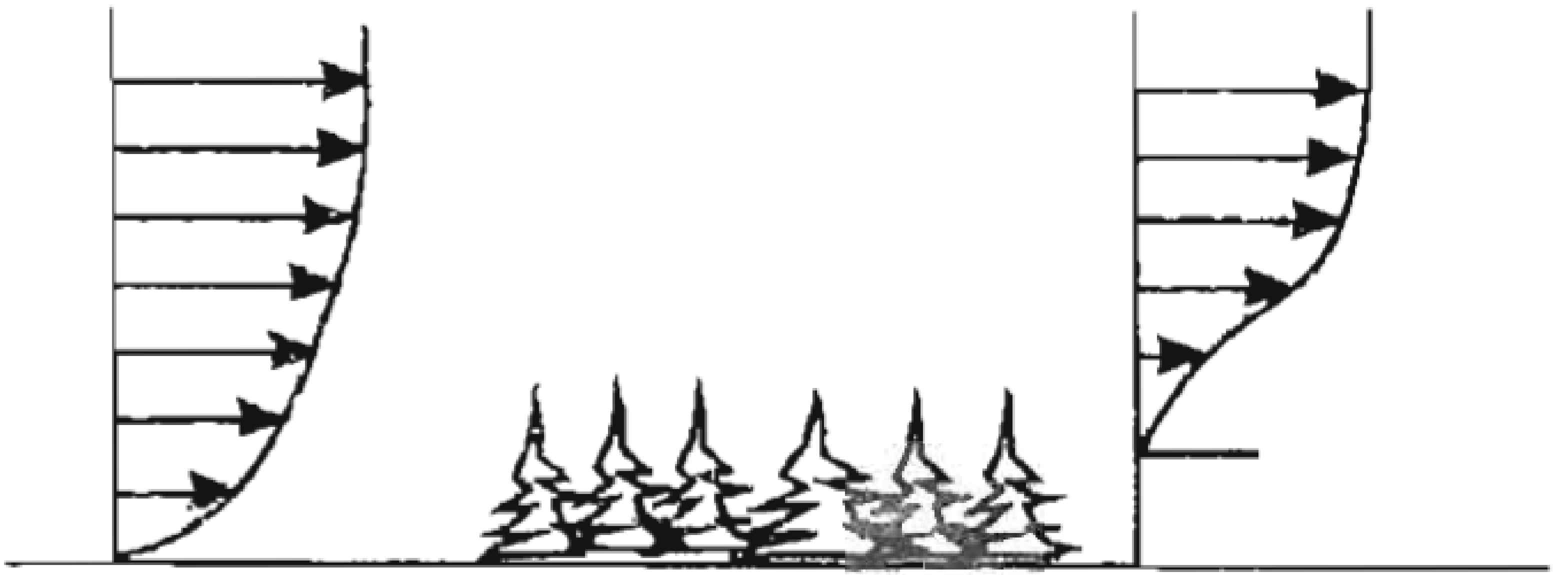
Determination of flat terrain (Wegley et al., 1980)

Flow over flat terrain with obstacles

Speed, power, and turbulence effects downstream of a building
(Wegley et al., 1980)



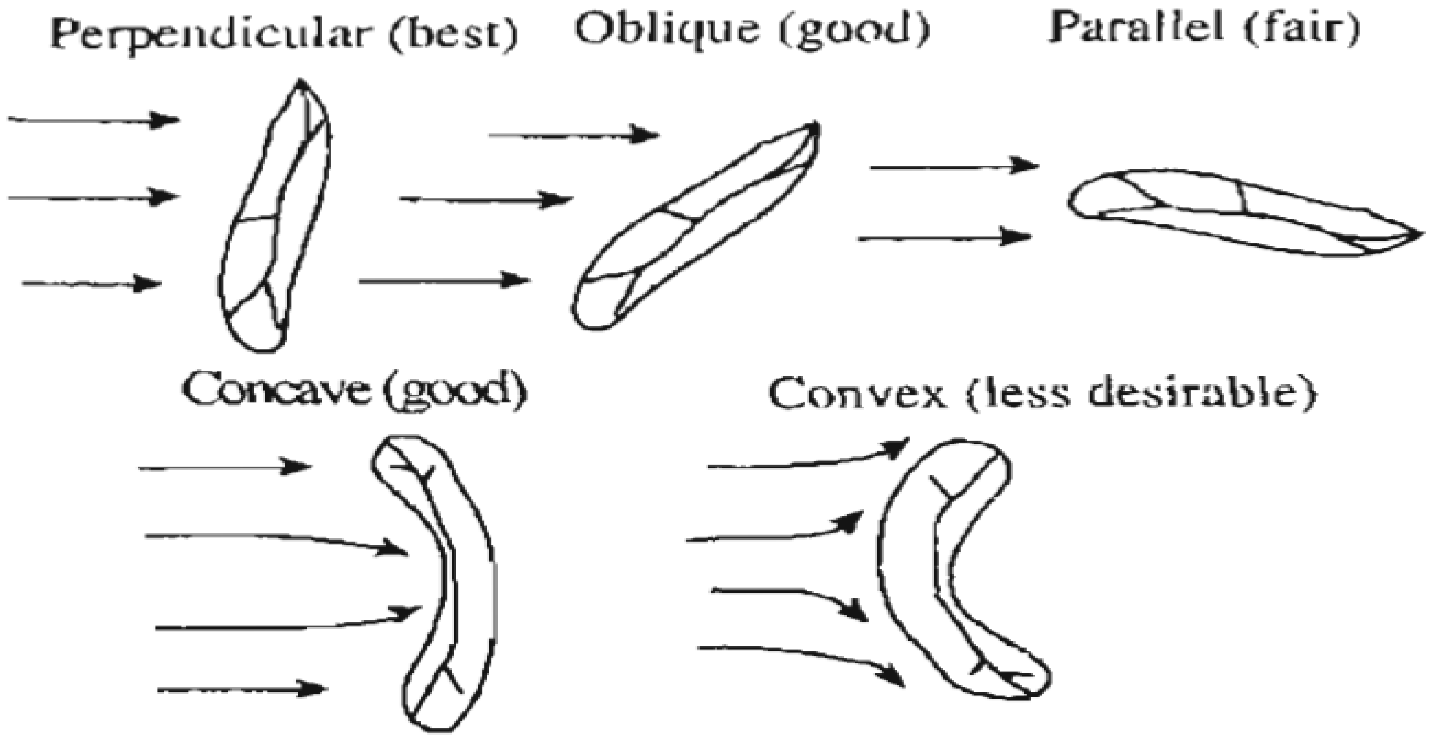
Flow in flat terrain with a change in surface roughness



Effect of change in surface roughness from smooth to rough on the wind profile (Wegley et al., 1980).

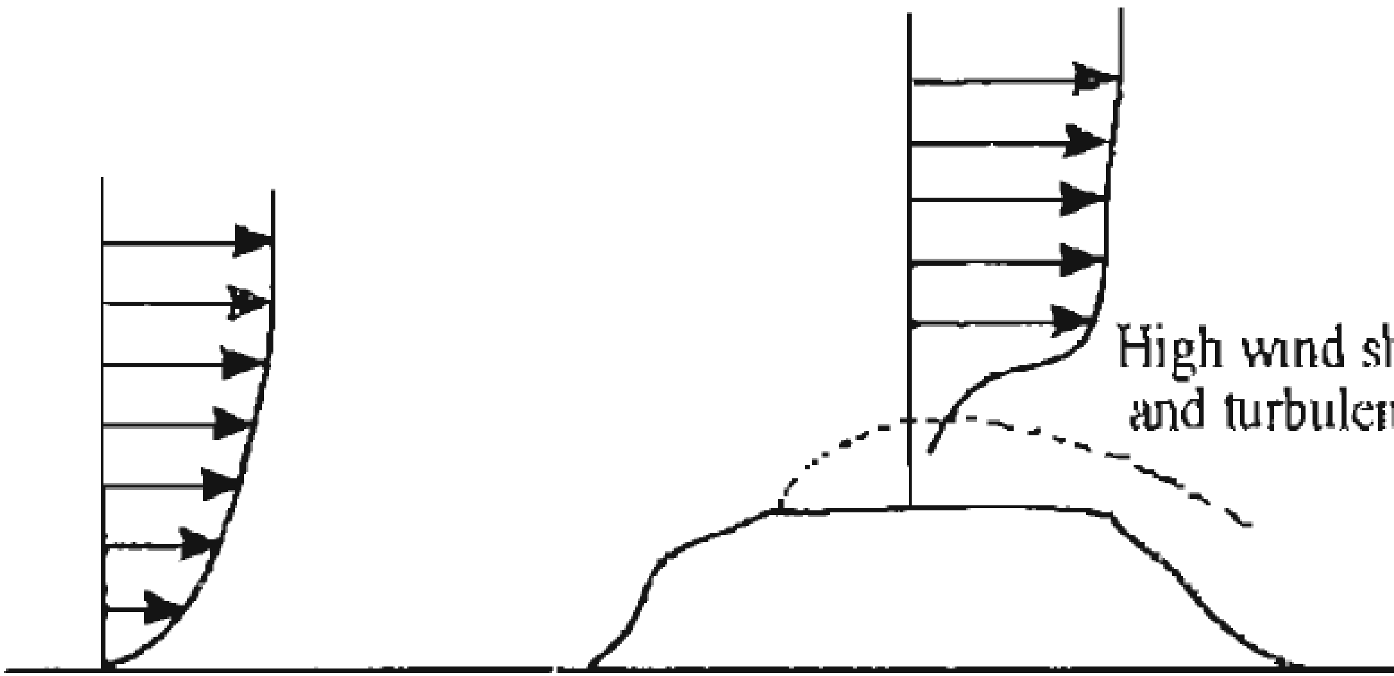
Flow in non-flat terrain, effect of ridges

Ridges are elongated hills that are less than 600m above the surrounding terrain and have non flat area on the summit. The ratio of length to height is at least 10



Effect of ridge orientation and shape on site suitability (Wegley et al., 1980)

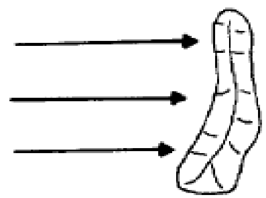
Flow over a flat-topped ridge



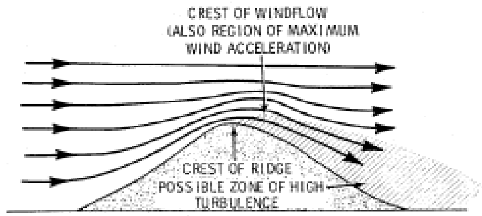
Region of high wind shear over a flat topped ridge (Wegley et al., 1980)

Suitable terrain features

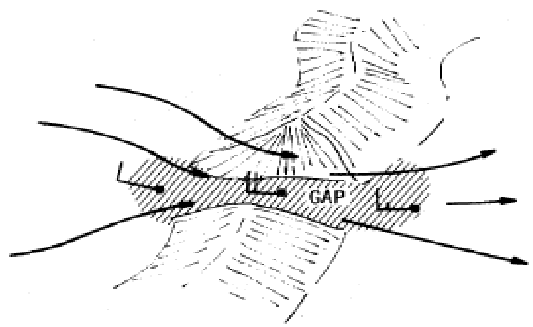
- Ridges oriented perpendicular to the prevailing wind direction



- Highest elevations within a given area



- Locations where local winds can funnel.



Unsuitable terrain features

- Features to be avoided include areas immediately upwind and downwind of higher terrain, the lee side of ridges, and excessively sloped terrain.

- In each of these situations, increased turbulence may occur.

Use of topographic maps

Aside from the features above, topographic maps also provide the analyst with a preliminary look at other site attributes including:

- Available land area
- Positions of existing roads and dwellings
- Land cover (e.g. forests)
- Political boundaries
- Parks
- Proximity to transmission lines

Field surveys and site ranking

Visits should be conducted to all potentially suitable areas. Items of importance include:

- Available land area
- Land use
- Location of obstructions
- Trees deformed by persistent strong winds
- Accessibility into the site
- Potential impact on local aesthetics
- Cellular phone service reliability for data transfers
- Possible wind monitoring locations

Challenges

PO Box 54224, Abu Dhabi,
United Arab Emirates, Tel +971 2 810 9130, ijanajreh@masdar.ac.ae

Transportation and installation:

- Road (2.6x4.1m)
- Crane system for all components and helicopter platform
- Simplified installation, i.e. telescoping or local assembling!

Offshore installation much less constrained!

Basic parameters to measure

Basic Measurement Parameters

Measured Parameters	Monitoring Heights
Wind Speed (m/s)	10 m, 25 m, 40 m
Wind Direction (degrees)	10 m. 25 m, 40 m
Temperature (°C)	3 m

These nominal parameters are recommended to obtain the basic information needed to evaluate resource-related wind energy feasibility issues

Optional parameters

Optional Measurement Parameters

Measured Parameters	Monitoring Heights
Solar Radiation (W/m^2)	3 - 4 m
Vertical Wind Speed (m/s)	38 m
Delta Temperature (°C)	38 m 3 m
Barometric Pressure (kPa)	2 - 3 m

Barometric pressure is used with air temperature to determine air density.

Basic and Optional Parameters

Measured Parameters	Recorded Values
Wind Speed (m/s)	Average Standard Deviation Maximum/Minimum
Wind Direction (degrees)	Average Standard Deviation Maximum Gust Direction
Temperature (°C)	Average Maximum/Minimum
Solar Radiation (W/m^2)	Average Maximum/Minimum
Vertical Wind Speed (m/s)	Average Standard Deviation
Barometric Pressure (hPa)	Average Maximum/Minimum
Delta Temperature (°C)	Average Maximum/Minimum

* Shaded parameters are optional

The measured parameters represent internal processing functions of the data logger.

All parameters should be sampled once every one or two seconds and recorded as averages, standard deviations, and max and min values

Specifications

Specifications for Basic Sensors

Specification	Anemometer (Wind Speed)	Wind Vane (Wind Direction)	Temperature Probe
Measurement Range	0 to 50 m/s	0° to 360° (≤8° deadband)	-40° to 60°C
Starting Threshold	≤1.0 m/s	≤1.0 m/s	N/A
Distance Constant	≤4.0 m	N/A	N/A
Operating Temperature Range	-40° to 60°C	-40° to 60°C	-40° to 60°C
Operating Humidity Range	0% to 100%	0% to 100%	0% to 100%
System Error	≤3%	≤5°	≤1°C
Recording Resolution	≤0.1 m/s	≤1°	≤0.1°C

Specifications

Specifications for Optional Sensors

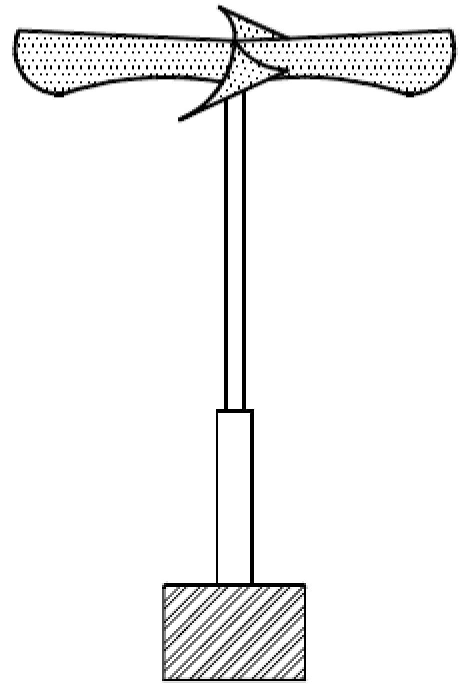
Specification	Pyranometer (Solar Radiation)	W Anemometer (Vertical Wind Speed)	ΔT Sensors (Delta Temperature)	Barometer (Atmospheric Pressure)
Measurement Range	0 to 1500 W/m^2	0 to 50 m/s	-40 to 60°C	94 to 106 kPa (sea level equivalent)
Starting Threshold	N/A	≤1.0 m/s	N/A	N/A
Distance Constant	N/A	≤4.0m	N/A	N/A
Operating Temperature Range	-40 to 60°C	-40 to 60°C	-40 to 60°C	-40 to 60°C
Operating Humidity Range	0 to 100%	0 to 100%	0 to 100%	0 to 100%
System Accuracy	≤5%	≤3%	≤0.1°C	≤1 kPa
Recording Resolution	≤1 W/m^2	≤0.1 m/s	≤0.01°	≤0.2 kPa

Wind measurement and instrumentation

Maximum cup anemometer

A transducer in the anemometer converts the rotational movement into an electrical signal, which is sent through a wire to a data logger.

Wind measurement and instrumentation

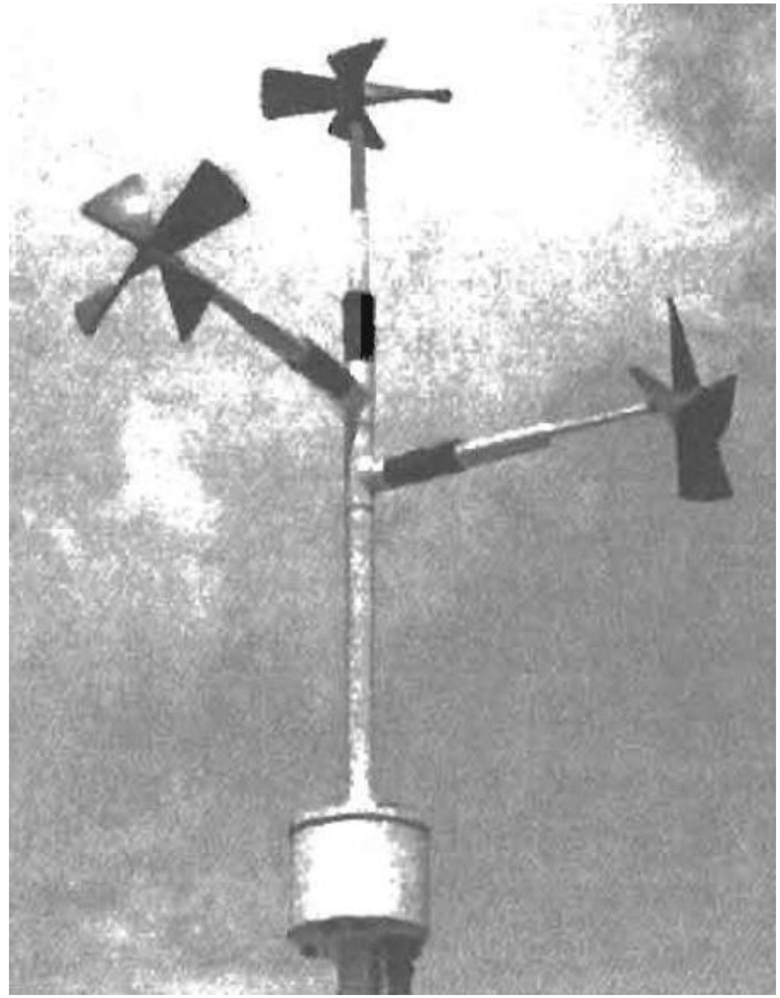


Propeller anemometer (or W anemometer)

Especially suited for measuring the vertical wind component

Wind measurement and instrumentation

Propeller type anemometer for measuring three wind velocity components



Wind measurement and instrumentation

Other instruments include:

- Sonic anemometers
- Acoustic doppler snesors (SODAR)
- Laser Doppler sensors (LIDAR)

Accuracy

Accuracy is typically expressed in three ways:

1. As a difference (as in, for temperature, $\leq 1^{\circ}C$), calculated as

$$\left(\textit{Measured Value} \ - \ \textit{Accepted Standard Value}\right)$$

2. A difference stated as a percentage of the accepted standard value (as in, for wind speed, $\leq 3\%$), calculated as

$$\left[\frac{\textit{Measured Value} \ - \ \textit{Accepted Standard Value}}{\textit{Accepted Standard Value}}\right](100)$$

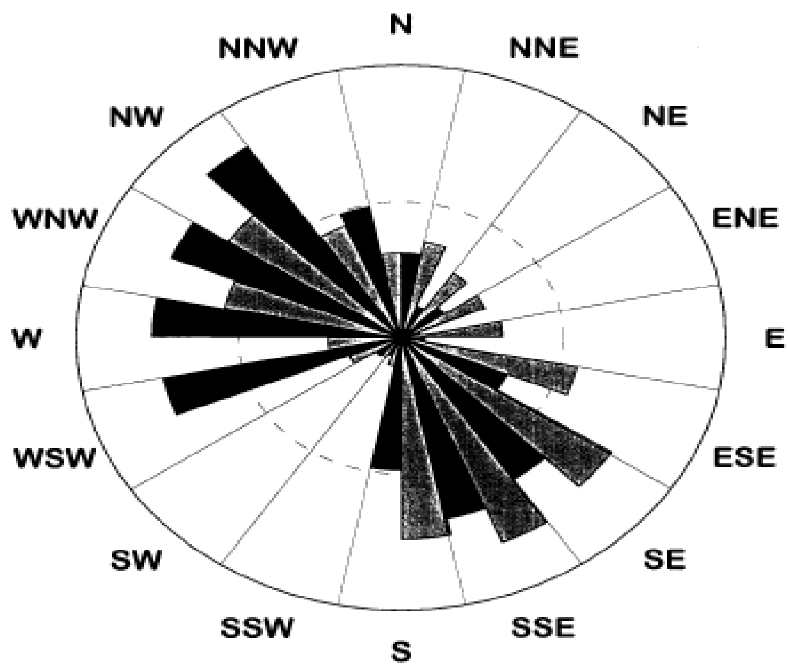
3. An agreement ratio stated as a percentage of the accepted standard value (as in, 95% accuracy), calculated as

$$\left[\frac{\textit{Measured Value}}{\textit{Accepted Standard Value}}\right](100)$$

Wind rose

SAMPLE MONTHLY DATA REPORTS

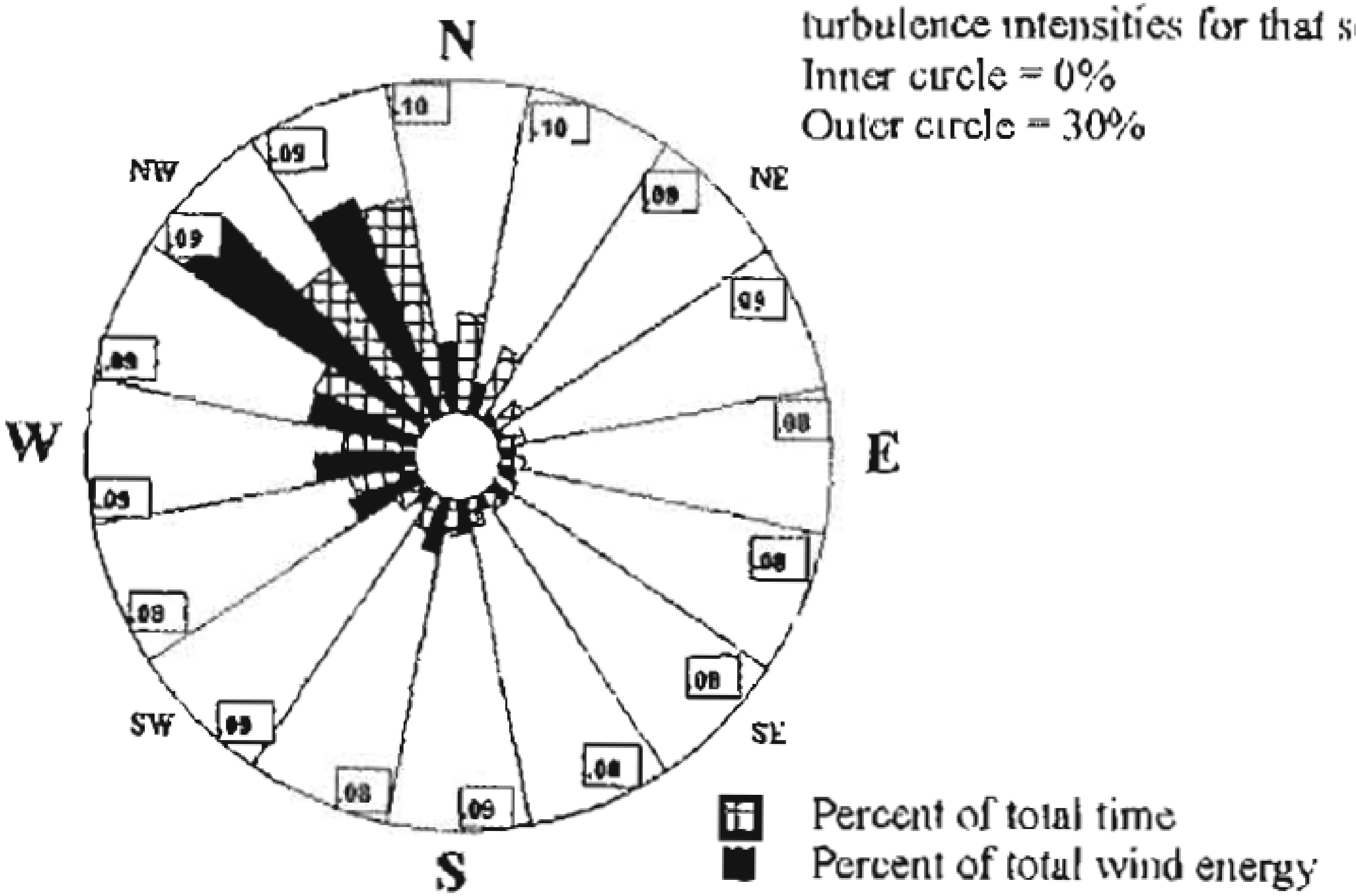
Wind Direction Frequency: Wind Rose



Percent of Total Wind Energy (Wh/m2):
Percent of Total Time:
Circle Center = 0.0%
Inner Circle = 7.5%
Outer Circle = 15.0%

Wind rose

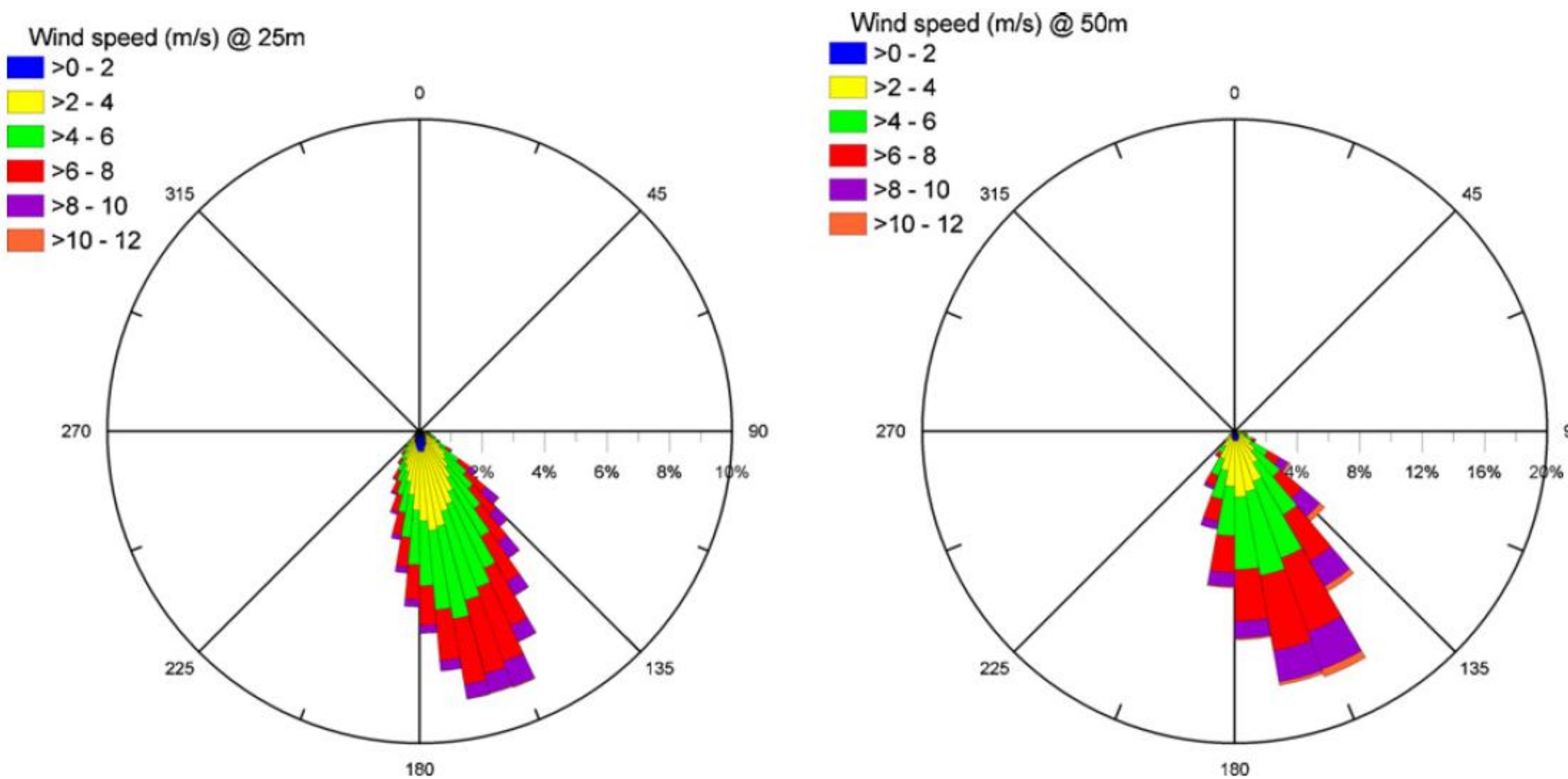
Example of a wind rose diagram



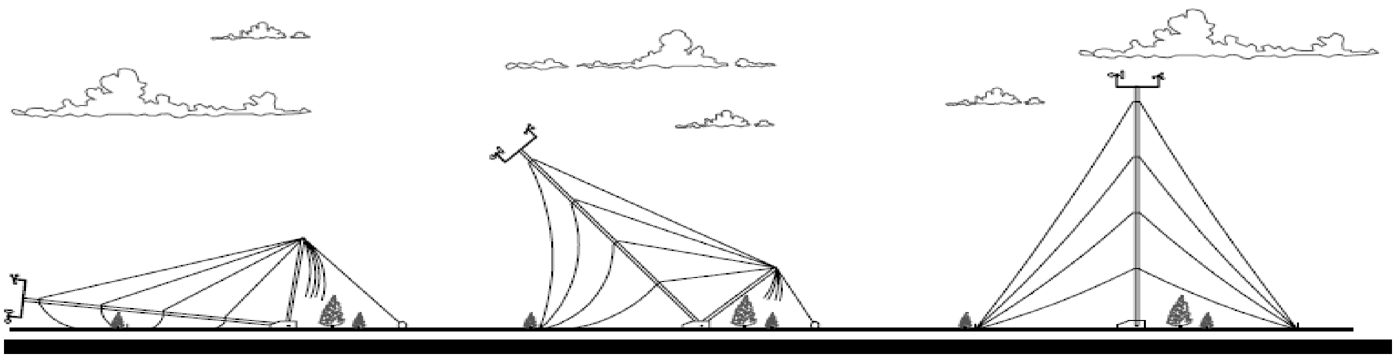
Outer numbers are averaged turbulence intensities for that sector
Inner circle = 0%
Outer circle = 30%

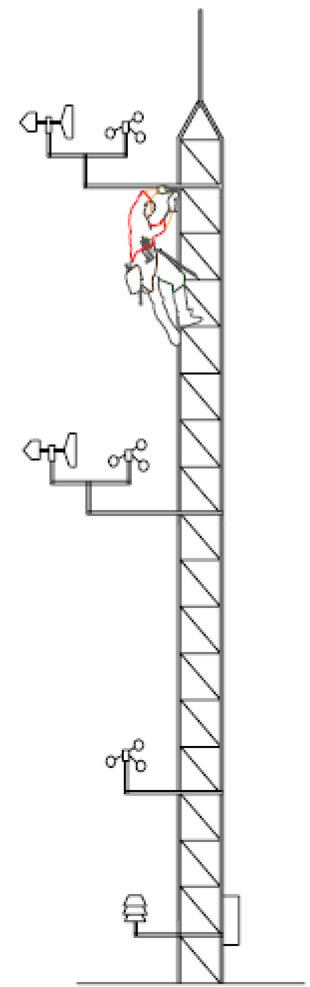
Wind rose

São João do Cariri wind rose at 25 and 50 m from SJC meteorological station.



Installation of monitoring stations



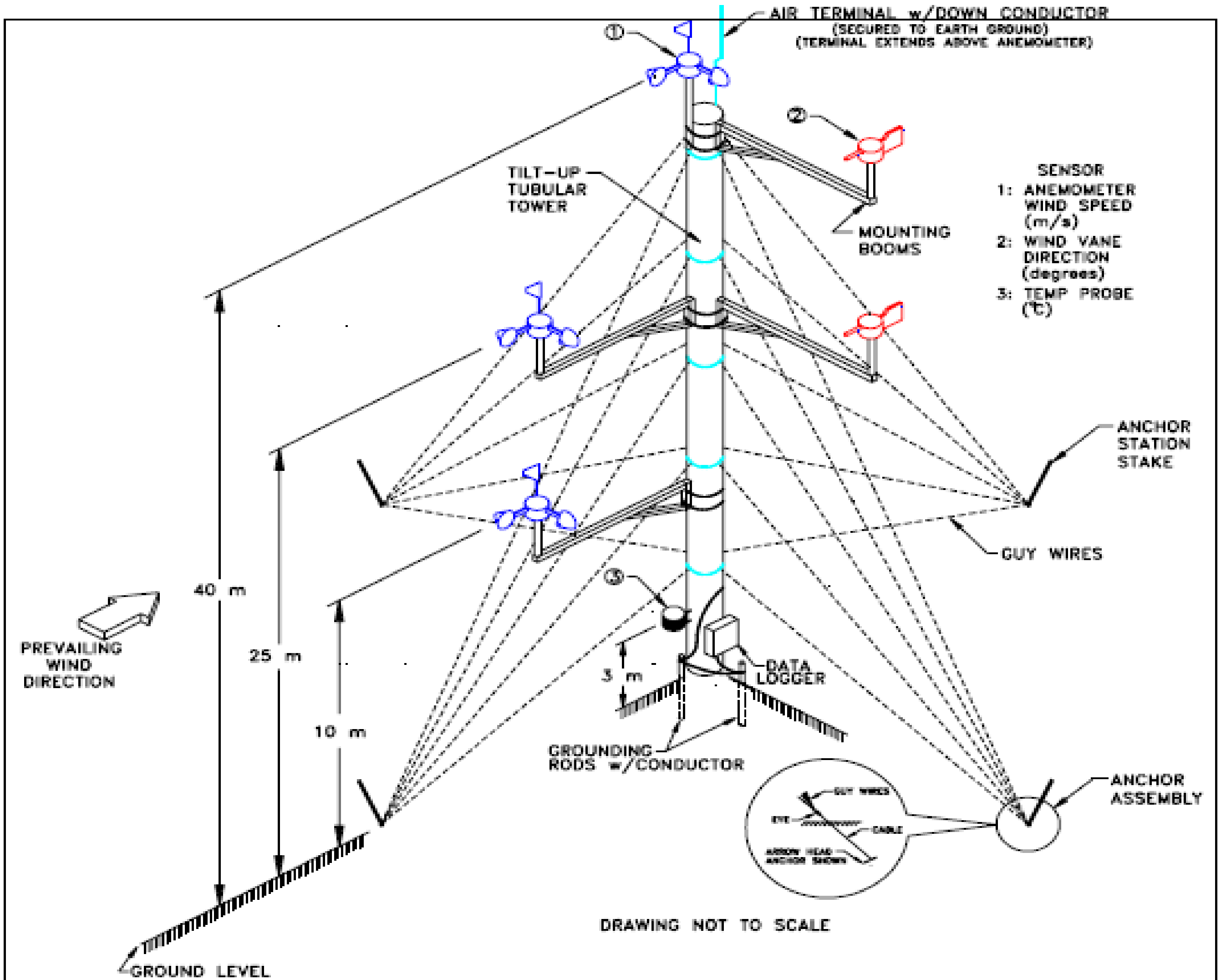


Soil Type and Recommended Anchoring System

Soil Type	Anchor Type	Installation Method
Loose to firm sand, gravel, or clay	Screw-in	Screw-in with crowbar
Soil with rocks	Arrowhead	Sledge or jack-hammer
Solid Rock	Pin / Rock Anchors	Drill hole and secure with epoxy/ expand with crowbar

Masdar INSTITUTE

Installation of monitoring stations



Sample Installation

Sample site information log

SAMPLE SITE INFORMATION LOG
(Cellular Site)

Form Revision Date:

Site Description	
Site Designation	
Location	
Elevation	
Installation/Commission Date	
Commission Time	
Soil Type	
Surroundings Description	
Prevailing Wind Direction	
Declination	

Site Equipment List						
Equipment Description	Mounting Height	Serial Number	Sensor Slope	Sensor Offset	Logger Terminal Number	Boom Direction (Vane Deadband)

Telecommunication Information	
ESN #	
Carrier	
Phone Number	
SYSID	
LOCAL	
MINMARK	
IPCH	
ACCOLC	
PRESYS	
GROUP	
Activation Date	

Contact Information	
Land Owner Name	
• Address	
• Phone Number	
Cellular Company	
• Phone Number	
• Contact Person	
• Contact's Extension	

Sample site visit checklist

SAMPLE SITE VISIT CHECKLIST
(Tilt-Tower / Cellular System)

A. GENERAL INFORMATION

Site Designation		
Site Location		
Crew members		
Date(s)		
Time (LST)	Arrival:	Departure:
Visit Type (Check)	Scheduled ☐	Unscheduled ☐
Work Scheduled		

B. IN-HOUSE PREPARATION

Check each box to denote the items have been acquired.

- ☐ In-house support person:______________________________
- ☐ Copy of Site Information Log.
- ☐ Acquire necessary tools, equipment, and supplies.
  - ☐ Electrical supplies: voltmeter, fuses, tape, connectors, cable ties, batteries, crimpers, etc.
  - ☐ Wrenches, pliers, screwdrivers, nut drivers, hex set, sledgehammer, wirecutters, etc.
  - ☐ Misc. equipment: silicon, magnetic level, binoculars, camera, GSP, etc.
  - ☐ Spare equipment: cabling, anchors, booms and mounting hardware, etc.
    - Sensors:
      (1) Sensor:__________ Serial #_________ Slope/Offset:______/______
      (2) Sensor:__________ Serial #_________ Slope/Offset:______/______
      (3) Sensor:__________ Serial #_________ Slope/Offset:______/______
    - Data logger: Serial Number_________
  - ☐ Road and topographic site maps.
  - ☐ Rental equipment: jackhammer w/compressor, truck/trailer, etc.
  - ☐ Winch with 12V battery and battery charger.
  - ☐ Gin pole and associated hardware.
  - ☐ Safety equipment: Hard hats, gloves, appropriate clothes, first aid kit, etc.
  - ☐ Manufacturer's manuals for installation and troubleshooting (sensors, datalogger, etc.)

Additional Information/Comments:____

C. GENERAL ON-SITE ACTIVITIES

Check the appropriate box. If No, provide an explanation below.

- **General Visual Inspection**
  - Yes ☐ No ☐ Area free of vandalism?
  - Yes ☐ No ☐ Tower straight?
  - Yes ☐ No ☐ Guy wires taut and properly secured?
  - Yes ☐ No ☐ Solar panel clean and properly oriented?
  - Yes ☐ No ☐ Wind sensors intact, oriented correctly, and operating?
  - Yes ☐ No ☐ Ice or snow on sensors, solar panel, antenna?
  - Yes ☐ No ☐ Grounding system intact?
  - Yes ☐ No ☐ Cellular antenna correctly orientated?

Findings/Actions:____

____

- **Data Retrieval**
  - Manual ☐ Remote ☐ Download method
  - Yes ☐ No ☐ Successful download? If No, provide explanation belos.

Findings/Actions:____

____

- **Datalogger Inspection** (Check when completed)
  - Yes ☐ No ☐ Data logger operational? If No, provide explanation below.
  - ☐ Record system voltages:______________________________
  - ☐ Date displayed:_ ________ Actual:_________ Corrected? (Circle) Yes / No
  - ☐ Time displayed:_________ Actual:_________ Corrected? (Circle) Yes / No
  - Yes ☐ No ☐ Check sensor values, are they reasonable? If No, provide explanation below.

Findings/Actions:____

____

- **Tower Lowering Activities**
  - Yes ☐ No ☐ Check all anchors, signs of movement?
  - Yes ☐ No ☐ Winch secured to anchor and safety line connected to vehicle bumper?
  - Yes ☐ No ☐ Gin pole assembled with safety cable and snaplinks taped?
  - Yes ☐ No ☐ Tower base bolt tight?
  - Yes ☐ No ☐ Gin pole safety rope attached and tensioned properly (gin pole straight)?
  - Yes ☐ No ☐ Weather conditions safe?
  - Yes ☐ No ☐ Note start time of tower lowering. ______________(CST)
  - Yes ☐ No ☐ Winch battery connected and terminals covered?
  - Yes ☐ No ☐ Lifting guy wire attachments to gin pole checked?

Findings/Actions:____

____

- **On-Ground General Activities**
  - Yes ☐ No ☐ Sensor and ground wires securely attached?
  - Yes ☐ No ☐ Grounding system intact and secure?
  - Yes ☐ No ☐ Sensor boom clamps secure?

C. GENERAL ON-SITE ACTIVITIES (Continued)

- **On-Ground General Activities** (Continued)

Yes ☐ No ☐ Boom orientation OK?
Yes ☐ No ☐ Boom welds OK?
Yes ☐ No ☐ Vane deadband orientation as reported on Site Information Log?
Yes ☐ No ☐ Sensors level and oriented correctly?
Yes ☐ No ☐ Sensor wire connections secure and sealed with silicon?
Yes ☐ No ☐ Signs of sensor damage?
Yes ☐ No ☐ Sensor outputs checked and functioning properly?
Yes ☐ No ☐ Sensor serial numbers as reported on Site Information Log?
Yes ☐ No ☐ Sensor and/or data logger replacement? If Yes:

- Sensors:

(1) Sensor:______ Serial #:______ Slope/Offset:______/______ Height:______
(2) Sensor:______ Serial #:______ Slope/Offset:______/______ Height:______
(3) Data Logger:______ Serial #:______

Findings/Actions:____

____

- **Tower Raising Activities**

Yes ☐ No ☐ Guy wire collars positioned correctly?
Yes ☐ No ☐ Lifting lines and anchor lines properly attached?
Yes ☐ No ☐ Gin pole secure, lines tensioned, gin pole straight, snap links taped?
Yes ☐ No ☐ Weather conditions safe?
Yes ☐ No ☐ Guys properly tensioned?
Yes ☐ No ☐ Tower straight?

- Note on-line time:__________(LST)

- **Site Departure Activities**

Yes ☐ No ☐ Successful data transfer with office computer?
Yes ☐ No ☐ Check antenna and phone connections?
Yes ☐ No ☐ Is datalogger date/time correct?
Yes ☐ No ☐ Secure datalogger enclosure with lock?
Yes ☐ No ☐ Clean area?
Yes ☐ No ☐ Guy wires clearly marked?

Findings/Actions:____

____

E. FINDINGS AND RECOMMENDATIONS

Yes ☐ No ☐ Further actions required? If Yes, describe below:

____
____
____
____
____
____

Data validation

Data Validation Flowchart

Raw Data Files

↓

Develop Data Validation Routines

General System and Measured Parameter Checks

- Range tests
- Relational tests
- Trend tests

Fine-tune Routines with Experience

↓

Validate Data

- Subject all data to validation
- Print validation report of suspect values
- Manually reconcile suspect values
- Insert validation codes
- Alert site operator to suspected measurement problems

↓

Create Valid Data Files

↓

Process Data and Generate Reports

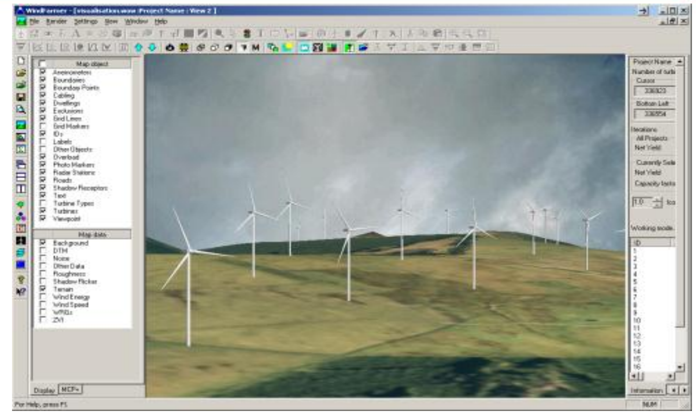
Costs and labor

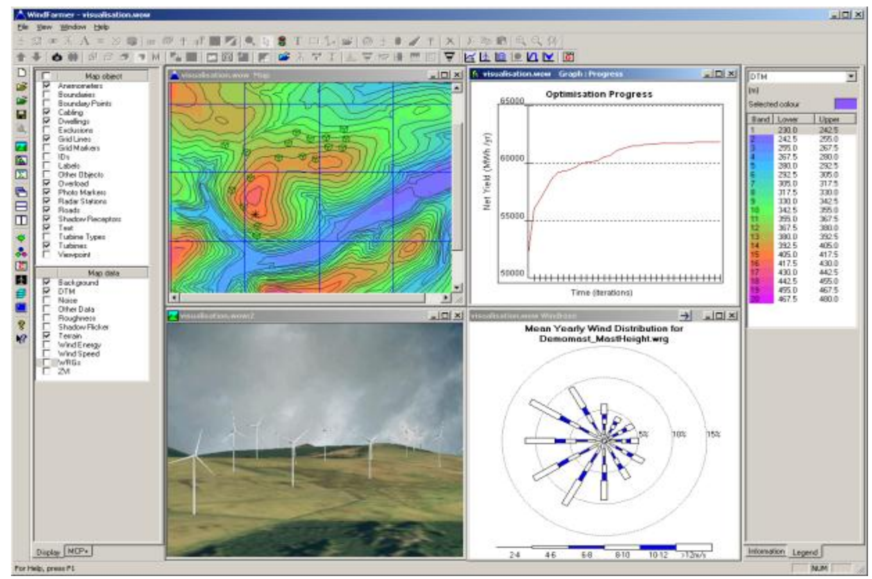
Labor Tasks to Account for When Budgeting

A. Administration
• Program oversight
• Measurement plan development
• Quality assurance plan development
B. Site Selection
• In-house remote screening
• Field survey & landowner contacts
• Obtain land use agreement & permit
C. Equipment
• Specify and procure
• Test and prepare for field
• Installation (two to three people)
D. Operation & Maintenance
• Routine site visits (one person)
• Unscheduled site visits (two people)
• Calibration at end of period
• Site decommissioning (two people)
E. Data Handling & Reporting
• Validation, processing & report generation
• Data and quality assurance reporting

Wind Farm Design Software - *WindFarmer*

- MCP analysis of measured wind data
- Energy yield prediction of planned wind farms
- Model effect of wakes from neighbouring turbines
- Automatically find optimum layout of turbines
- Calculate environmental impact
- Visualise completed wind farm





Masdar INSTITUTE