small wind good practice: small wind turbines case study integrated in a smart grid

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OVERVIEW

Wind energy exploitation is growing rapidly
Wind turbines have larger and larger size

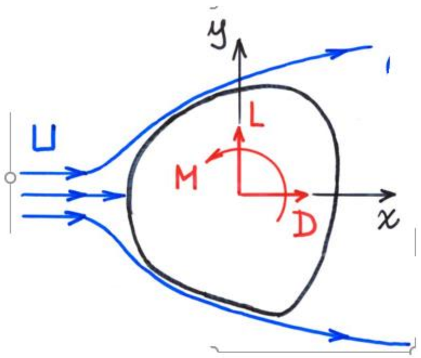
Small Size Wind Turbines
are less competitive: construction and operating costs are often high with respect to the power production

BUT *are* attractive from many points of view:

- small instabilities in the power network
- low environmental impact
  don't need large power storage capability
  suitable for distributed energy generation

✓ appropriate technology to develop the strategic aim of small-scale distributed generation energy systems in smart grid and smart city

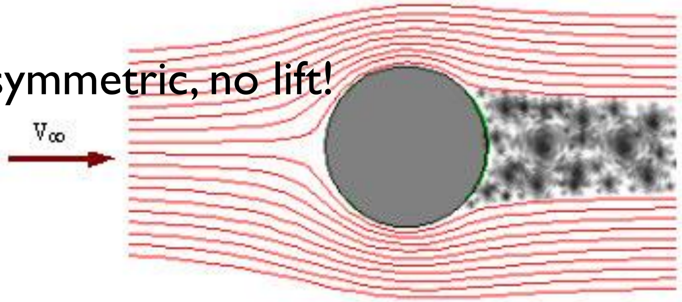
There are two forces in play: Lift and Drag. The **Lift Force** is perpendicular to the wind direction. It is caused by a pressure difference between the air on either side of the blade. The **Drag Force** is in the same direction as the wind. The ratio between lift and drag largely depends on the shape of the blade and the angle of the main line of the blade (chord line) and the main wind direction - the angle of attack.

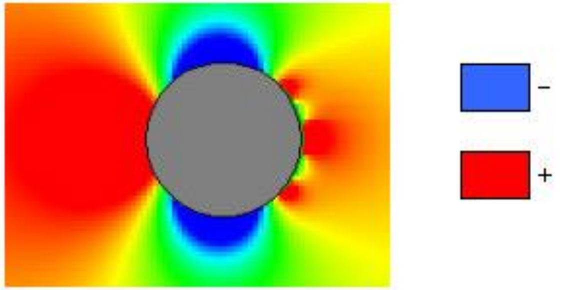


stream flow

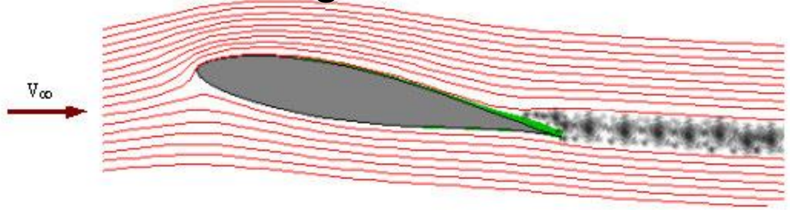
pressures

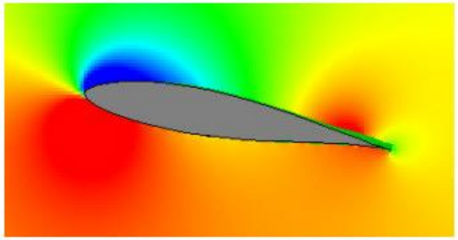
symmetric, no lift!

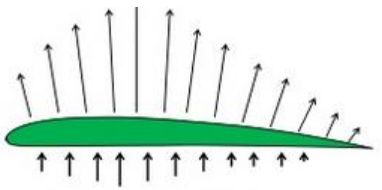




The lift force is largest for streamlined

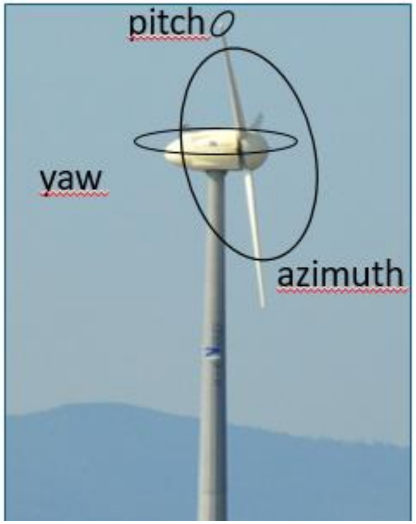






Depending on the design of the turbine, either drag or lift moves the blades.

Horizontal Axis Wind Turbines (HAWTs)



Main degrees of freedom

- **Azimuth**

–rotation of rotor about its shaft due to the torque

- **Yaw**

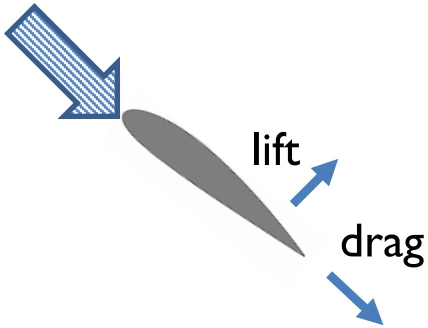
–rotation of nacelle about the vertical lengthwise axis of the tower

- **Pitch**

–rotation of blades about their lengthwise axis due to pitch control

Turbines based on lift force:

the wind is flowing on both sides of the blade, which has different geometrical profiles, thus creating at the upper surface a low pressure area with respect to the pressure on the lower face. This produces a lift force on the blade which rotates around the hub.



OVERVIEW

Horizontal Axis Wind Turbines (HAWTs)

- is the most common technology in use for large wind turbines

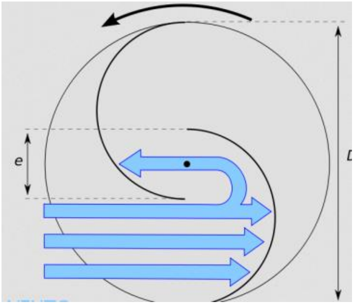
- need to be aligned with the direction of the wind, allowing the wind to flow parallel to the axis of rotation

- the rotor should always be perpendicular to the wind: a wind vane is mounted to measure the direction.
This signal is coupled with a yaw motor, which continuously turns the nacelle into the wind

Vertical Axis Wind Turbines (VAWTs)

Savonius Rotor

based on drag force



Darreus Rotor

H-type Darreus

based on lift force

Vertical Axis Wind Turbines (VAWTs)

- designed to act correspondingly towards air
- do not require any yaw mechanism, pitch regulation: few movable parts and lower maintenance costs.
- quite low rotating speed and thus producing low noise

have received less financial support

BUT

attractive for smaller size applications, especially in complex contexts like urban areas

VAWTs versus HAWTs

HAWT

Advantages

- ❑ Lower cut-in wind speed
- ❑ Higher efficiency
- ❑ Lower cost /power
- ❑ Ability to furl rotor out of wind

Disadvantages

- ❖ Active yaw drive
- ❖ Difficult maintenance
- ❖ Many moving parts

VAWT

Advantages

- ❑ no yaw mechanism
- ❑ no pitch regulation
- ❑ few movable parts → lower maintenance costs
- ❑ low rotating speed → produce low noise

Disadvantages

- ❖ Low wind speed
- ❖ Low efficiency
- ❖ Difficult over speed control
- ❖ Difficult starting

ISSUES

- ✓ **power curve**

Which is the actual behavior and power production?

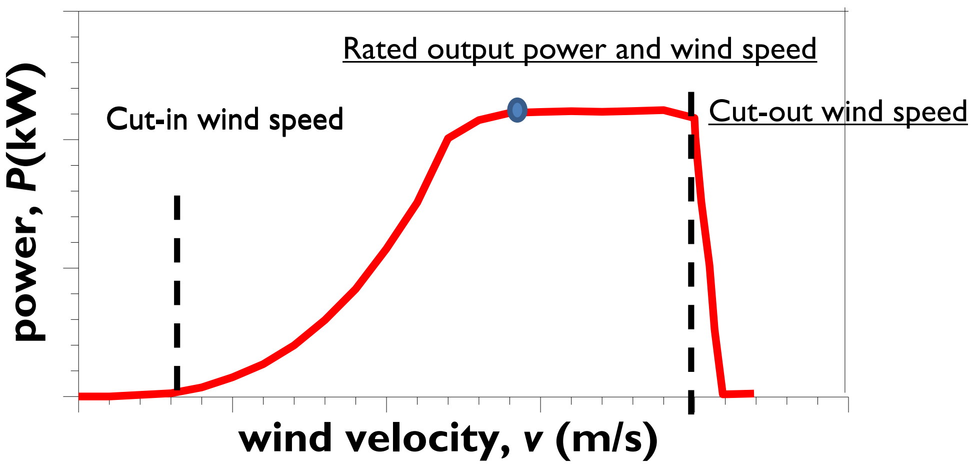
- ✓ **optimal planning of the mix of power production units**

competitive with other renewable sources? (e.g. PV solar)

- ✓ **structural response and safety:**

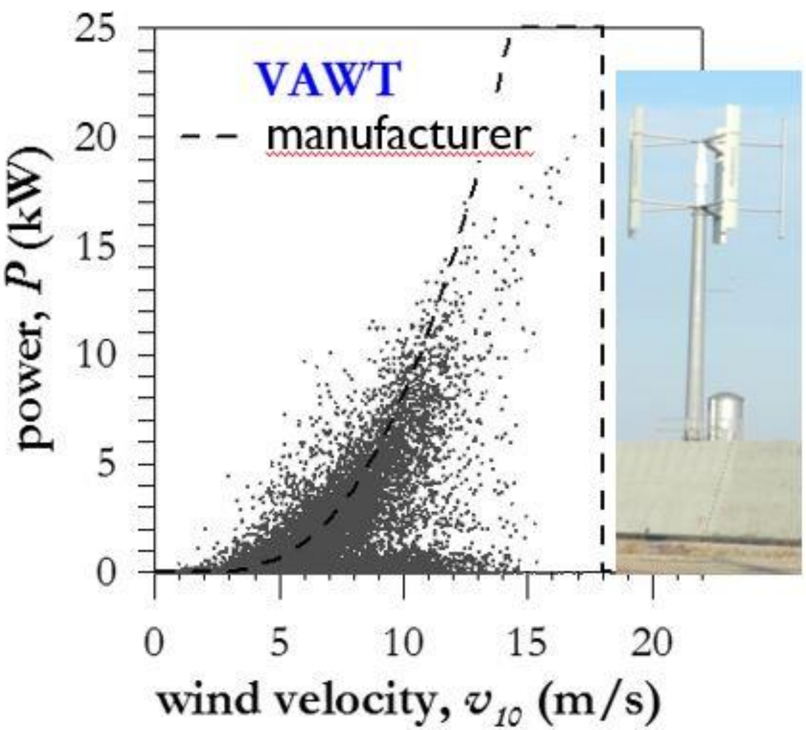
their behavior is as much complex as the behavior of the large size turbines. Which are major shortcomings that may concern structural safety?

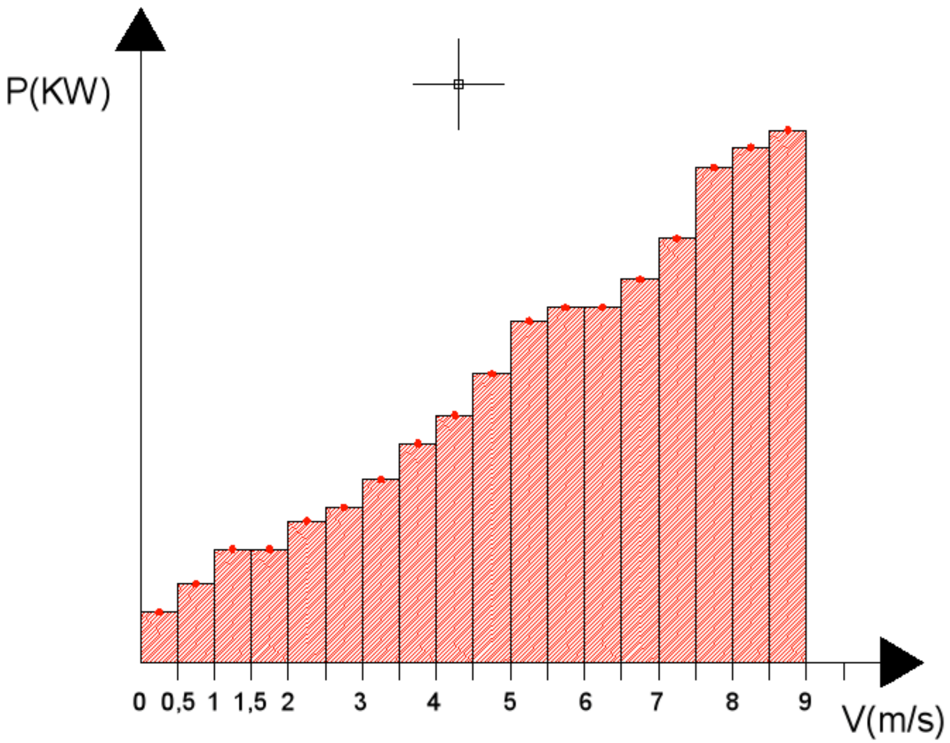
POWER CURVE



Cut-in wind speed - this is the minimum wind speed at which the turbine blades overcome friction and begin to rotate
Cut-out speed - This is the speed at which the turbine blades are brought to rest to avoid damage from high winds. Not all turbines have a well-defined cut-out speed.
Power curve - this is the steady power delivered by the turbine as a function of steady wind speed between the cut-in and cut-out speeds.

POWER CURVE





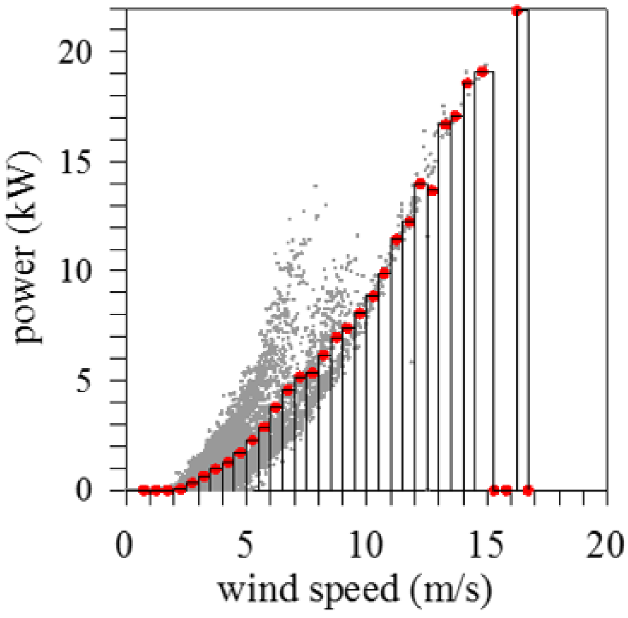
International Electrotechnical Commission, IEC 61400-12

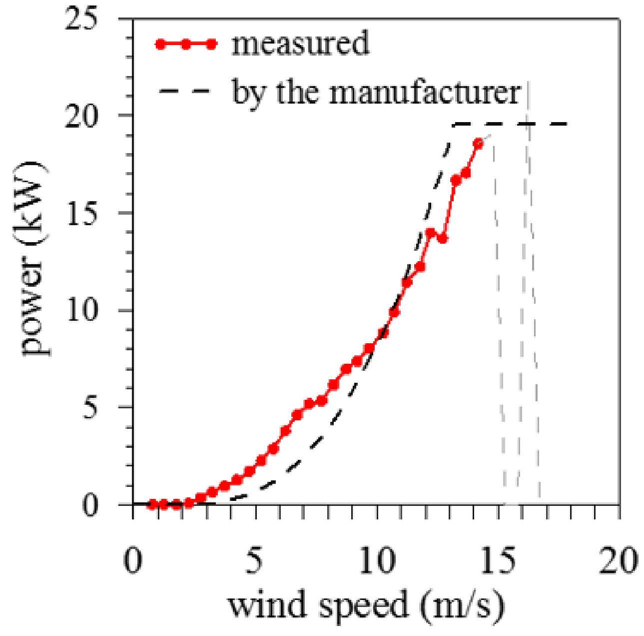
The measured power curve is determined by the **method of bins** calculating the mean values of the wind speed and power output for each wind speed bin

$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{n,1,j}$$

$$P_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P_{n,1,j}$$

Method of bins
(International Electrotechnical Commission, IEC 61400-12)

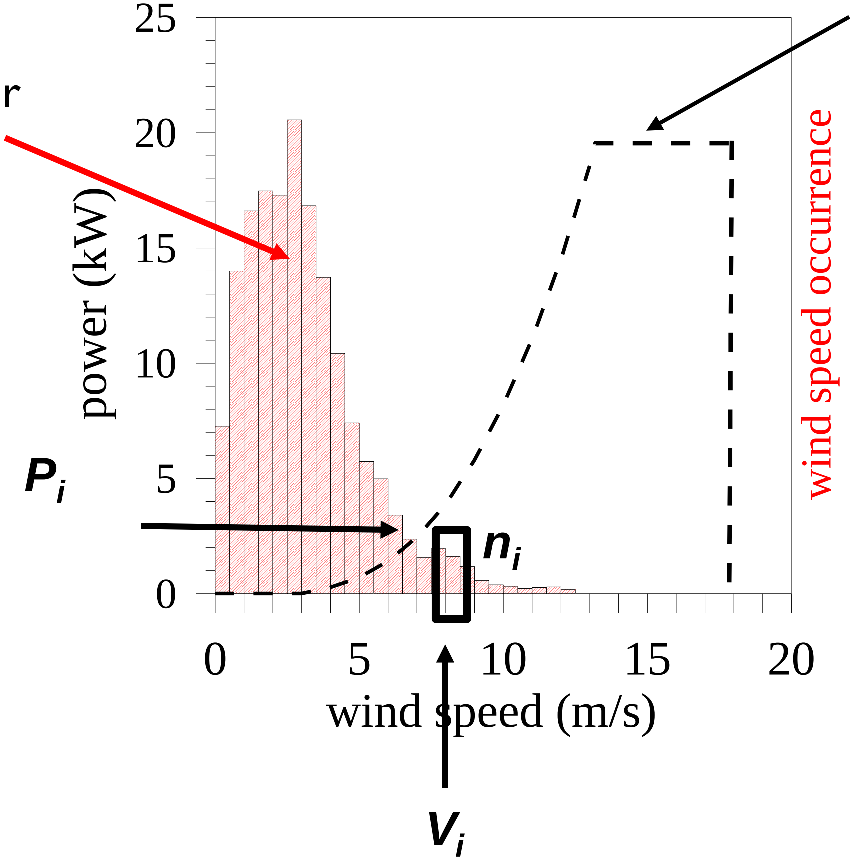




POWER CURVE

prevision of the yearly power production of a specific wind turbine

We can evaluate the energy production by combining the power curve with the histogram of the wind data.



$$E = \sum_i n_i P(v_i) \Delta t$$

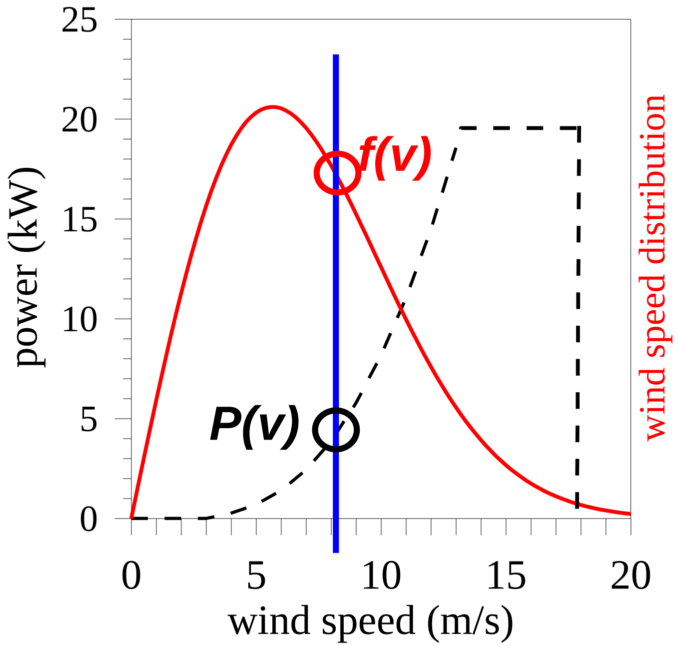
$$[kW \times 10\,\mathrm{min}]$$

$$E = \sum_i n_i P(v_i) \Delta t / 6$$

$$[kWh]$$

POWER CURVE

- The wind speed is a random variable we can represent by a Weibull distribution.
- By combining the power curve with the wind distribution, the actual energy production is yielded, often expressed in terms of the annual energy production: E_{year}



$$E = N_0 \int_0^{\infty} P(v) \cdot f(v) \cdot dv$$

[kW h]

$P(u)$	power curve function **[kW]**
$f(u)$	wind distribution function
V_{start}	cut-in wind speed
V_{stop}	cut-out wind speed
N_0	= 8765 hours/year

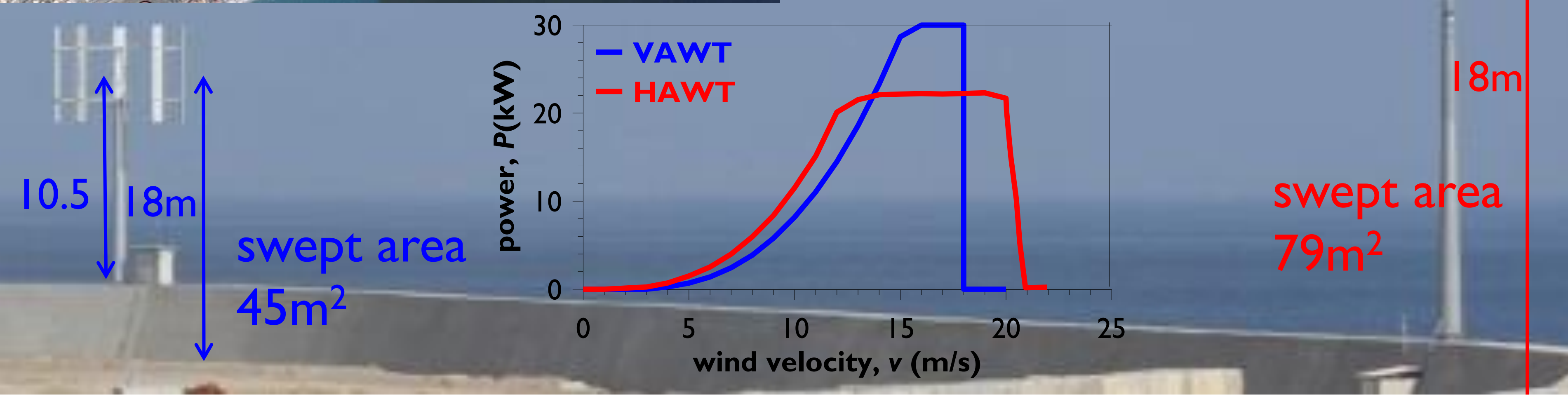
POWER CURVE

experimental activity with Port Authority of Savona

Two small size wind turbines
20 kW HAWT
20 kW VAWT (de-rated)

installed in 2012

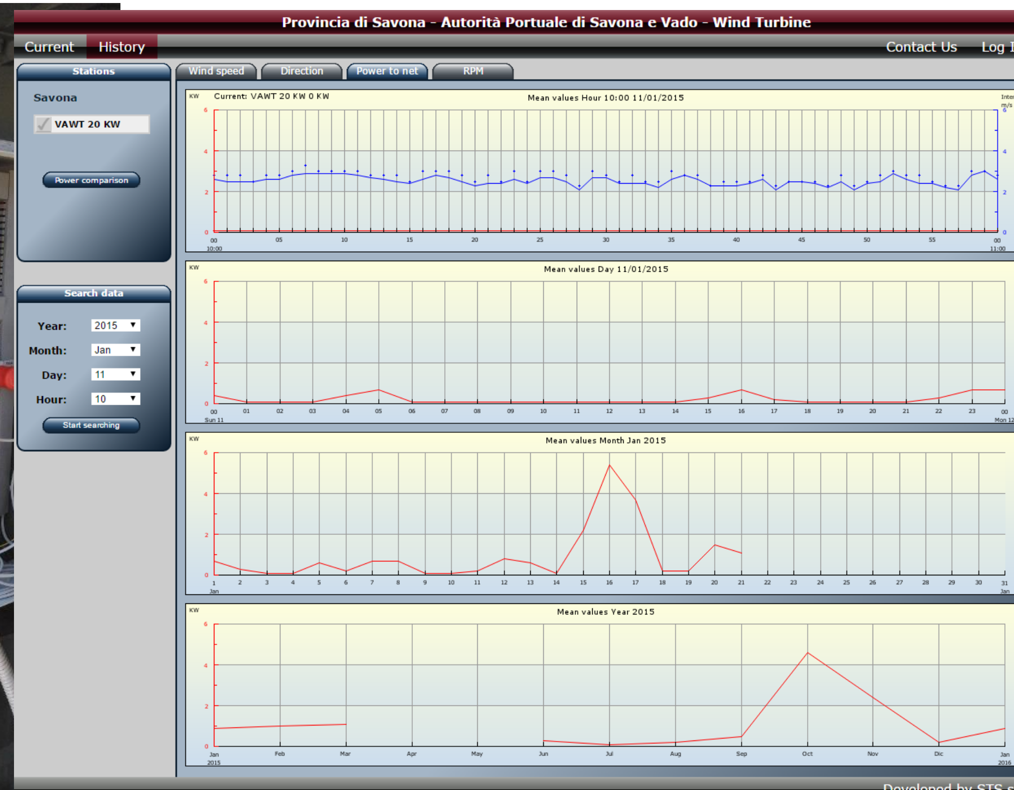
renewed in 2014



power to net and blade rotation speed monitoring

power, rpm, wind speed (cup anemom.), direction

integrated power control system – sampling rate: 0.1 Hz

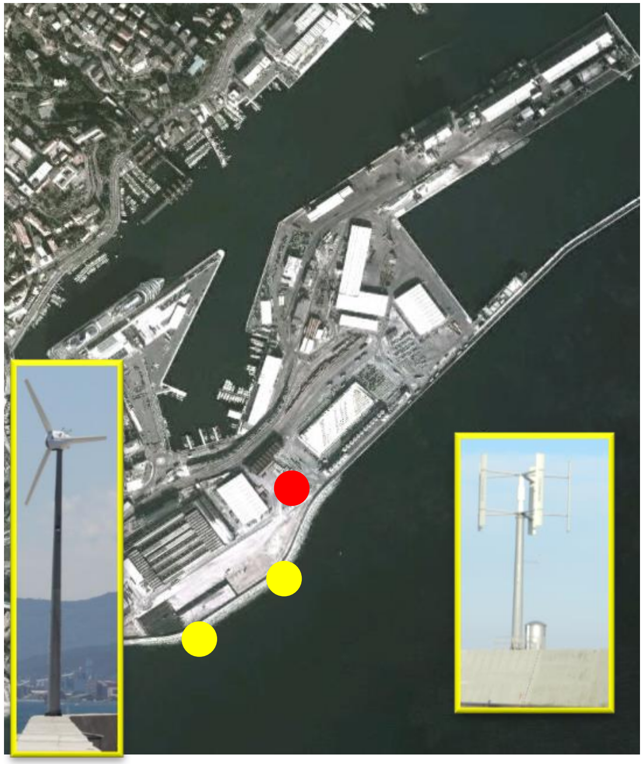


POWER CURVE

wind monitoring

cup anemometer
sampling rate: 0.1 Hz

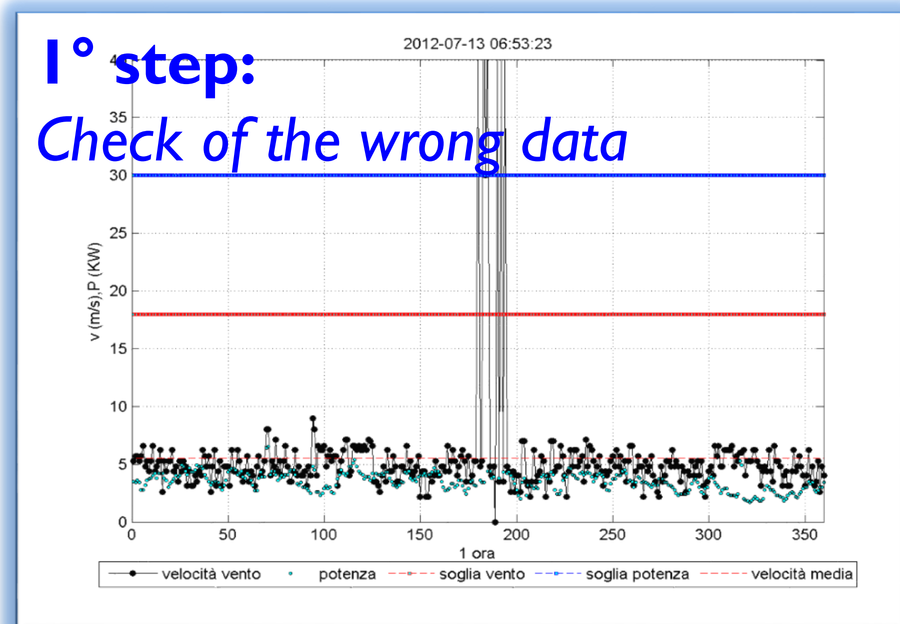
sonic anemometer
sampling rate: 10 Hz



data base and transfer to the turbine hub
(sonic anemometer)

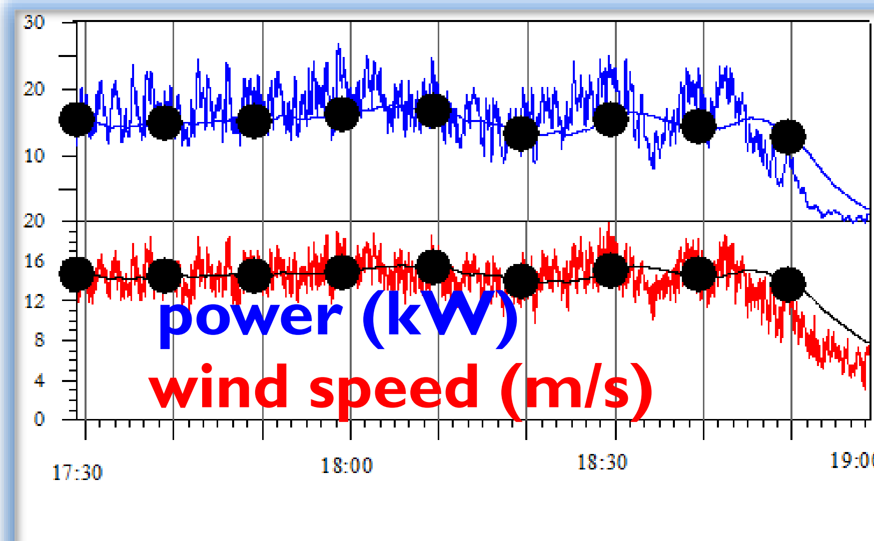
1° step:

Check of the wrong data



2° step:

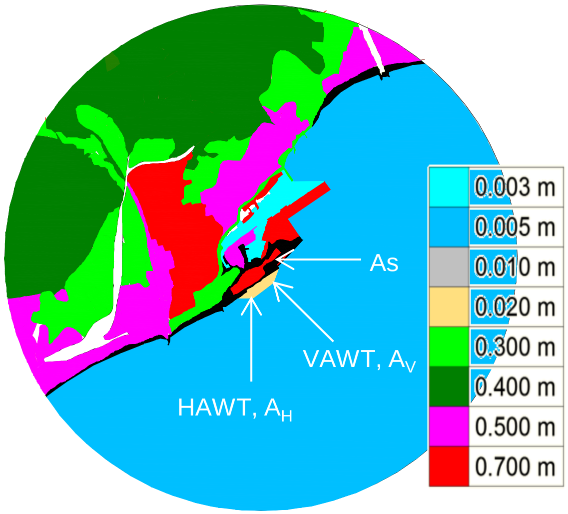
Average over 10-minutes power, velocity, direction, turbulence intensity



3° step:

Transfering wind to the turbine

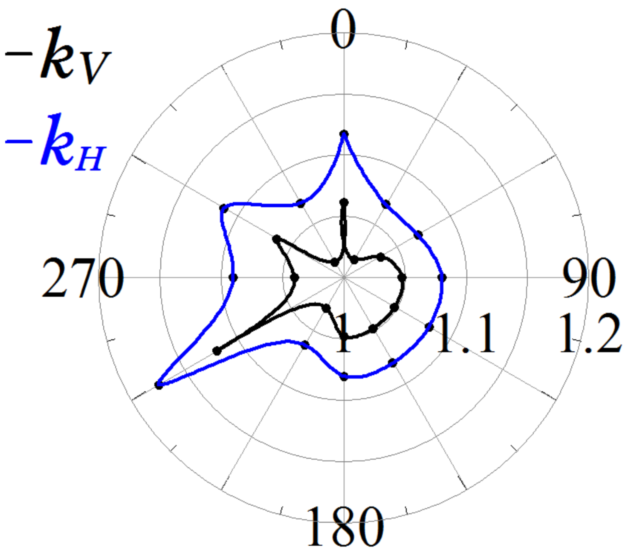
POWER CURVE



3° step:
Transfering wind to the turbine

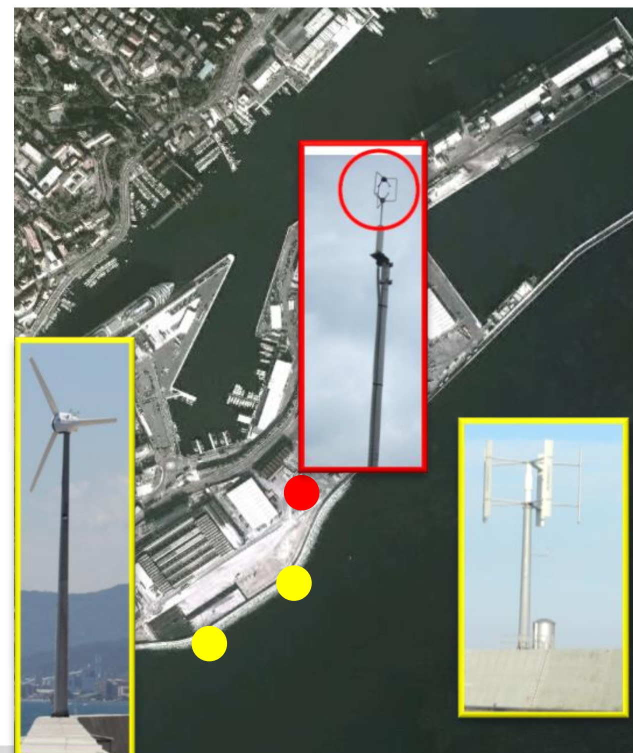
roughness model of the surroundings (ESDU)

transfer coefficients

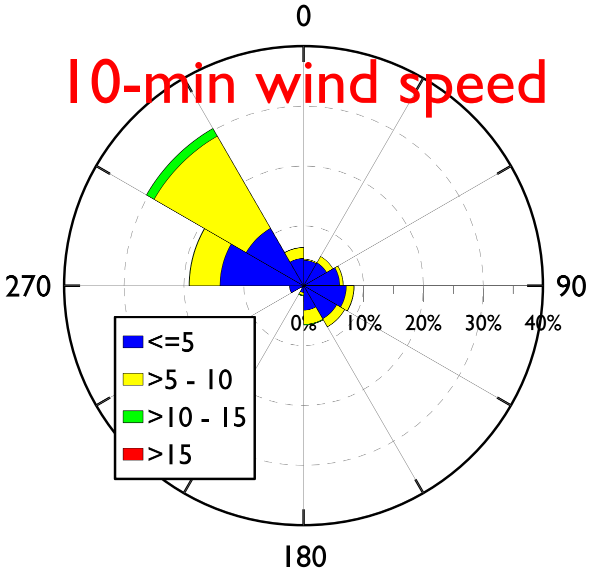


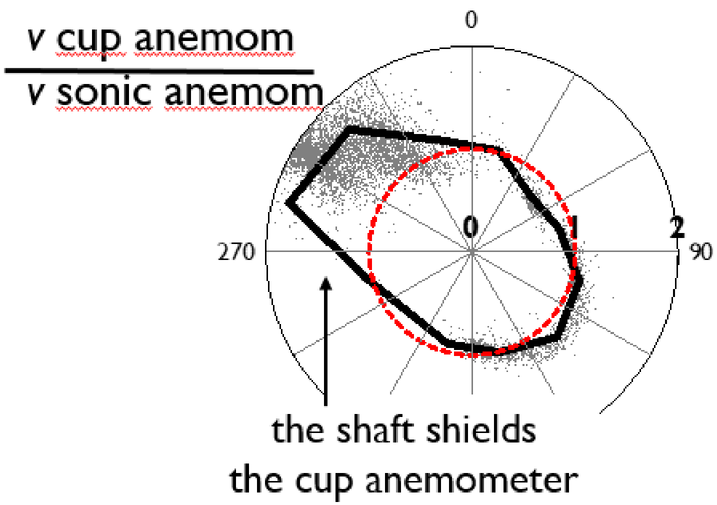
time series recorded by the sonic anemometer are transferred to the rotor by simulating the roughness the surroundings for each direction of the incoming wind

$$v_{VAWT}(\alpha)=k_V(\alpha)\times v_S(\alpha)$$
$$v_{HAWT}(\alpha)=k_H(\alpha)\times v_S(\alpha)$$



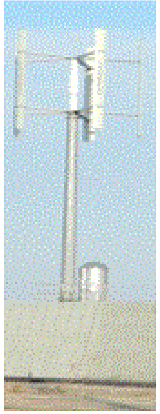
POWER CURVE



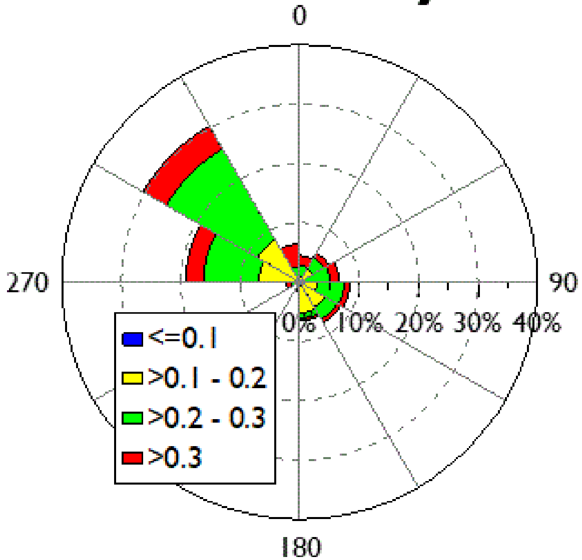


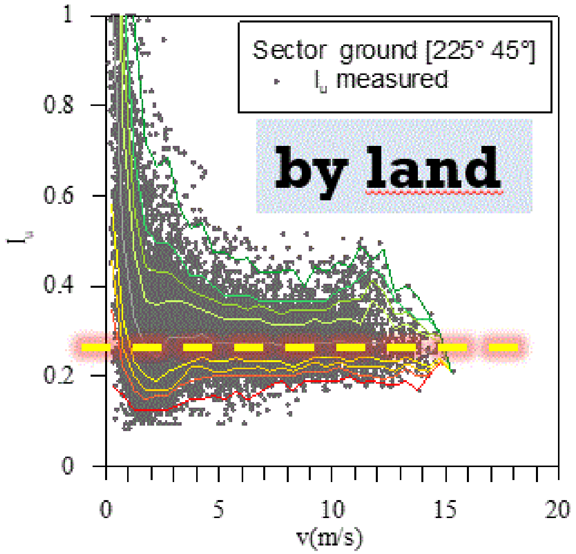
This is a mistake one can still find in the field of small turbines

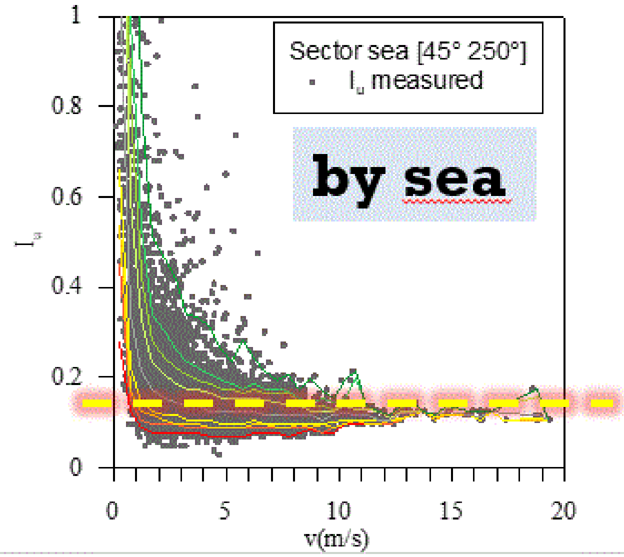
Pagnini, Burlando and Repetto (2015) **Experimental power curve of small-size wind turbines in turbulent urban environment**, *Applied Energy*, 154

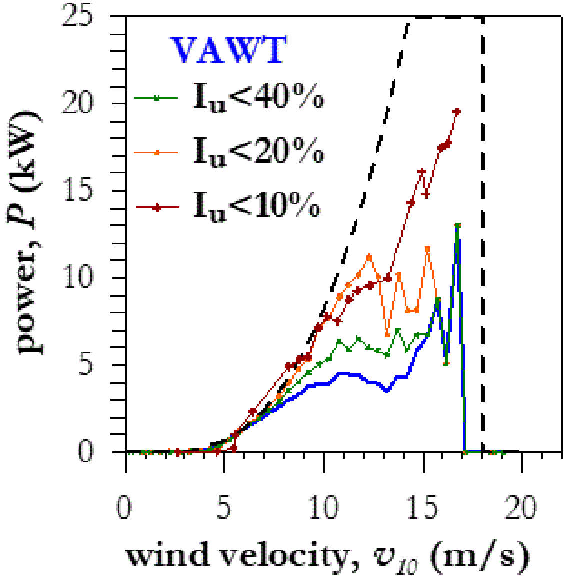


turbulence intensity





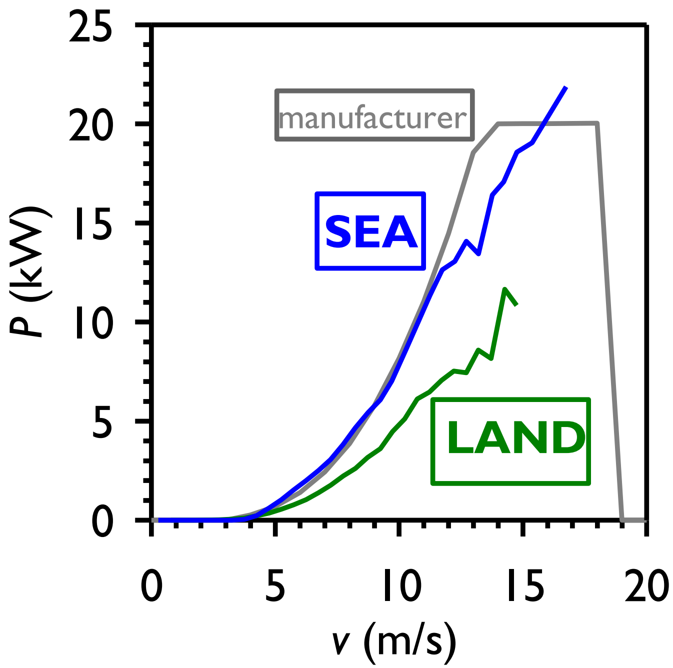


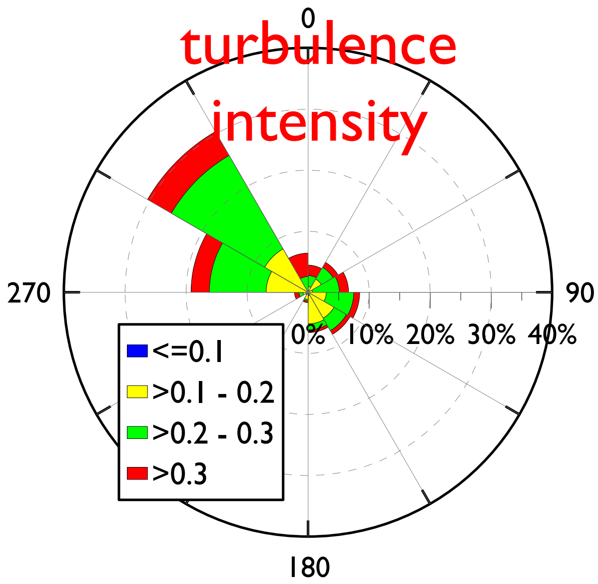


POWER CURVE

Dataset 2016

VAWT

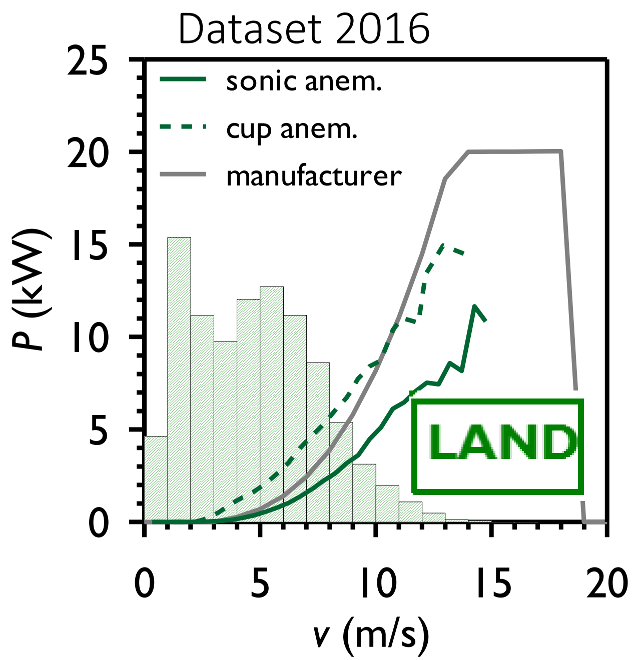


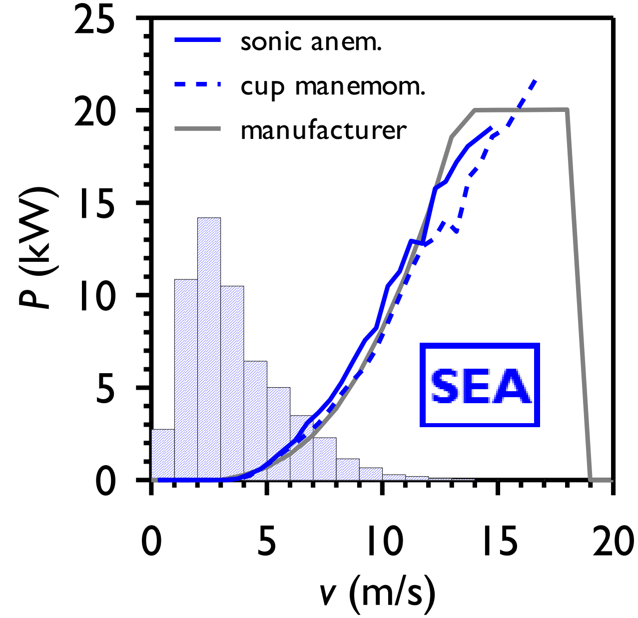


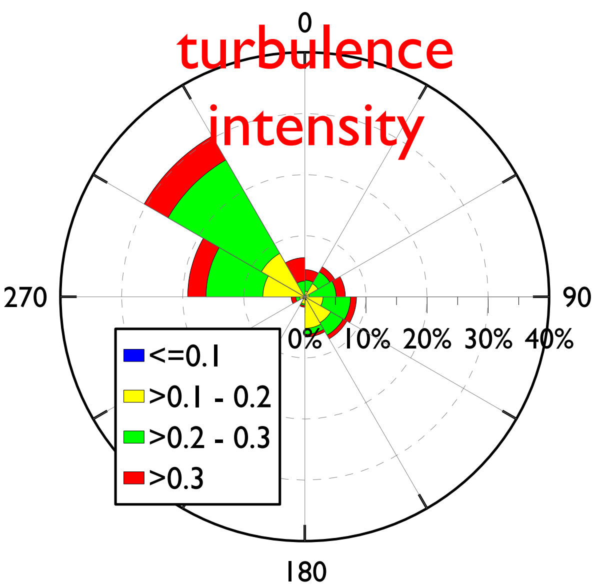
- ❑ performance is almost in line with expectations when wind is blowing from sea sectors
- ❑ detrimental effect of high turbulence when wind is blowing from land
- ❑ unfortunately, it is the prevalent condition

Experimental power curve

VAWT





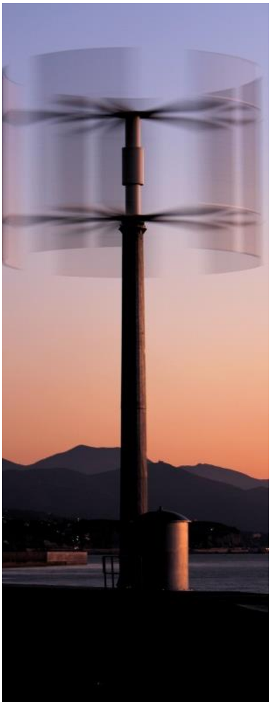


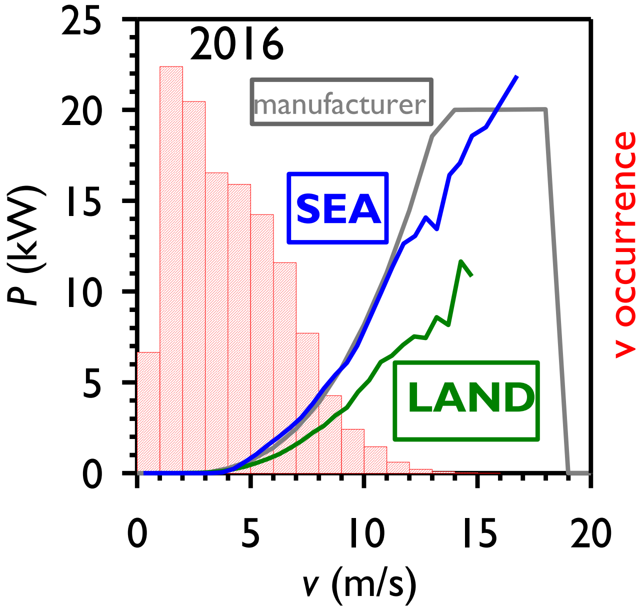
- The power curve derived from the cup anemometer is completely misleading.
- A better positioning of the anemometer, exposed to the prevailing wind directions, would have enabled to capture the most significant data.
- This makes us reflect on some common mistakes in the field of small turbines

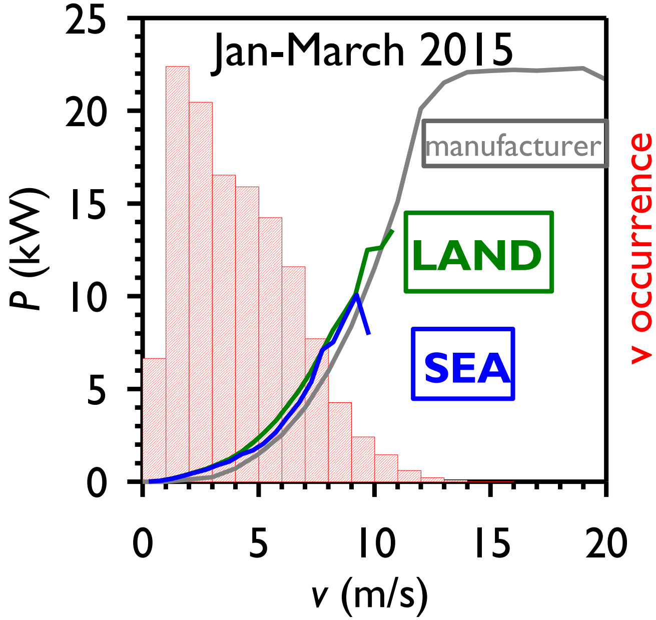
POWER CURVE

cost and production

$$E = 8760 \int_0^{\infty} P(v) \cdot f(v) \cdot dv$$







VAWT	(2016)		HAWT	(2014)
produced	expected		produced	expected
8MWh	15MWh		11 MWh	24 MWh

many out of use - dismantled in 2015

SMALL SIZE WTS: MIX PLANNING

in smart cities it is necessary to optimally manage energy sources and end-user needs

considering: distributed generation / intermittent renewables / storage / grid constraints

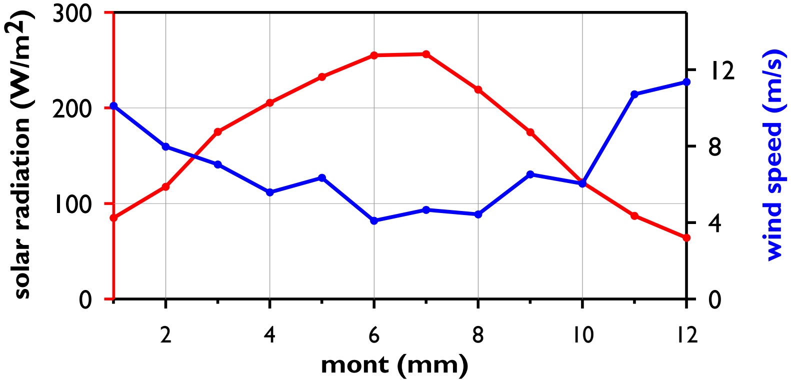
and: the daily and seasonal variation of the renewable source and of the electrical demand

The Savona Campus - University of Genova

courses of engineering, medical and social sciences

SMALL SIZE WTS: MIX PLANNING

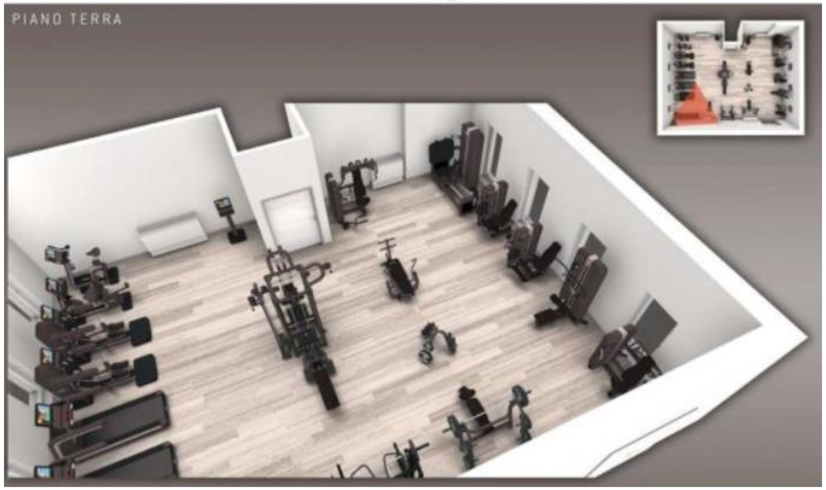
The Savona Campus - University of Genova
courses of engineering, medical and social sciences



integrated power producton between PV solar and wind

SMART ENERGY BUILDING

completely powered by renewable sources
Includes a gymnasium where users
produce electrical power feeding the electrical grid



SMALL SIZE WTS: MIX PLANNING

Smart Polygeneration Microgrid (SPM) of Savona Campus - University of Genova

plug-in electrical vehicles

chiller : waste heat into cooling energy

control room

concentrated solar power

gas turbine

storage

referring to the SPM as the technical application, a decision model is applied for the planning of the energy production mix in the smart grid feeding the Campus

micro gas turbines, CHPs

Combined Heat and Power units producing both electrical and thermal power

solar PV units

SMALL SIZE WTS: MIX PLANNING

decision variables - at site *s* year *y*, month *m*, daily hour *t*

$S^{PV}_{s,\alpha}$ [m²]: surface covered by PV panels with tilt α;

n^{w}_{s} : number of WTs

$n^{CHP}_{s,\beta}$: number of micro-turbines

costs and benefits of the grid

$$C^{Grid}_{s,y,m,t} = \underbrace{c^{el}_{s,y,m,t} E^{IN}_{s,y,m,t}}_{\text{cost power purchased from the grid}} - \underbrace{b^{el}_{s,y,m,t} E^{OUT}_{s,y,m,t}}_{\text{benefit power sold to the grid}}$$

cost power purchased from the grid

benefit power sold to the grid

costs and maintainance of the units

$C^{CHP}_{s,y,m,t}$ $C^{PV}_{s,y,m,t}$ $C^{W}_{s,y,m}$

Maintenance

SMALL SIZE WTS: MIX PLANNING

optimization of the object function:
installation costs + annual discounted operating costs

Installation costs: → Annual discounted operating costs

$$\min\left\{K+\sum_{y=1}^{Y}\frac{C_y}{(1+i)^y}\right\}$$

PV surface installed in site s inclined α

Number of microturbines (CHP) of kind β in site s

Number of wind turbines in site s

$$K=\sum_{s=1}^{S}\left(\sum_{\alpha=1}^{N_\alpha}k_\alpha^{PV}S_{s,\alpha}^{PV}\delta_{s,\alpha}^{PV}+\sum_{\beta=1}^{N_\beta}k_\beta^{CHP}n_{s,\beta}^{CHP}+k^{W}n_s^{W}\right)$$

Unit costs

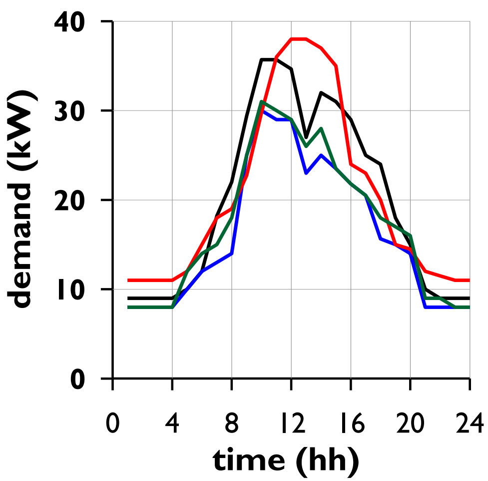
$$C_y=\sum_{s=1}^{S}\sum_{m=1}^{M}\left[n_m\sum_{t=0}^{T-1}\left(C_{s,y,m,t}^{GRID}+C_{s,y,m,t}^{CHP}+C_{s,y,m,t}^{PV}+C_{s,y,m}^{W}\right)\right]$$

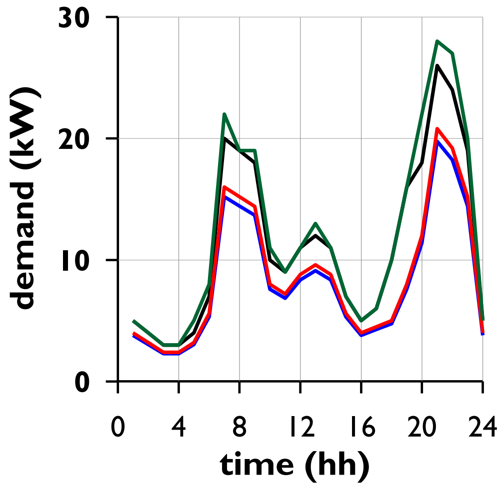
Number of days in month *m*

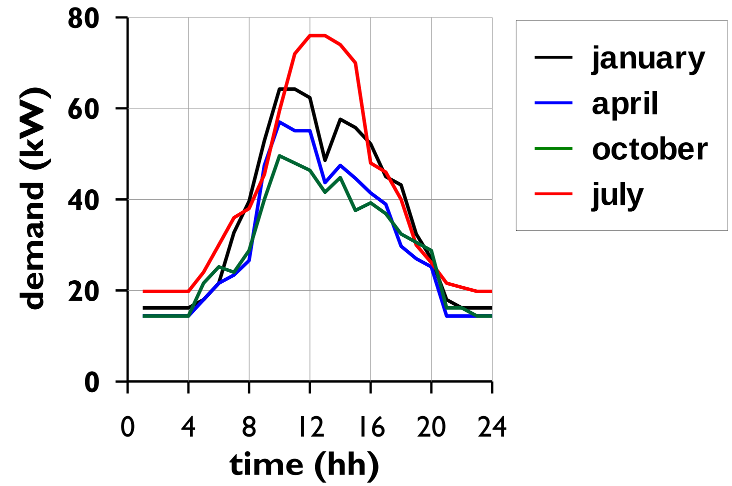
for grid purchase, microturbines, photovoltaics, and wind turbines: maintainance

SMALL SIZE WTS: MIX PLANNING

Hourly electricity demand - hour *h*, month *m*







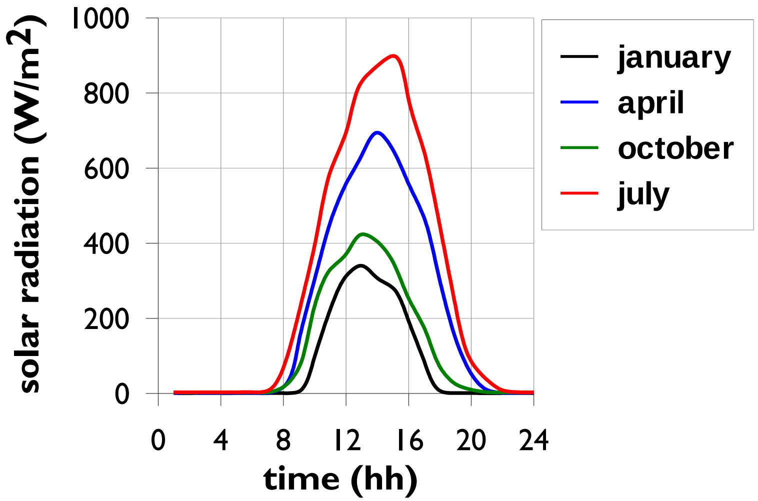
OFFICES building n°1

STUDENT HOUSING

OFFICES building n°2

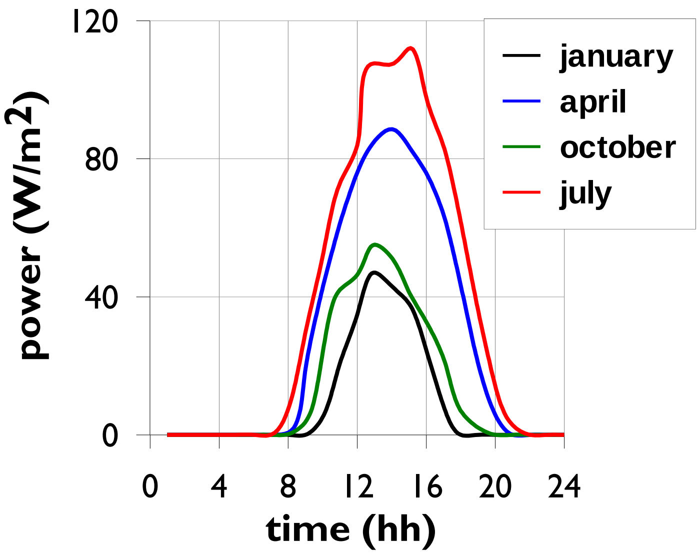
SMALL SIZE WTS: MIX PLANNING

hourly solar radiation - hour *h*, month *m*



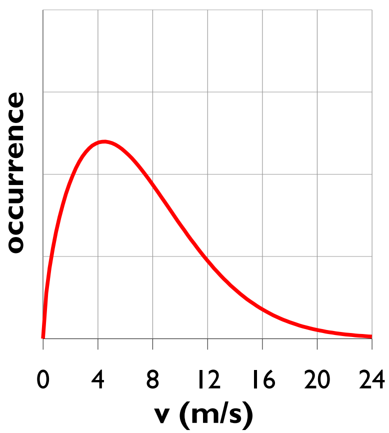
hourly power generated - PV

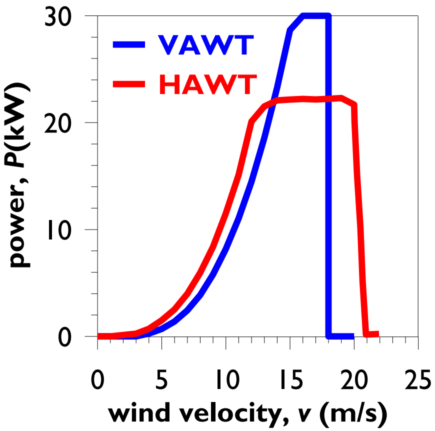
tilt angle 0°
azimuth 180°



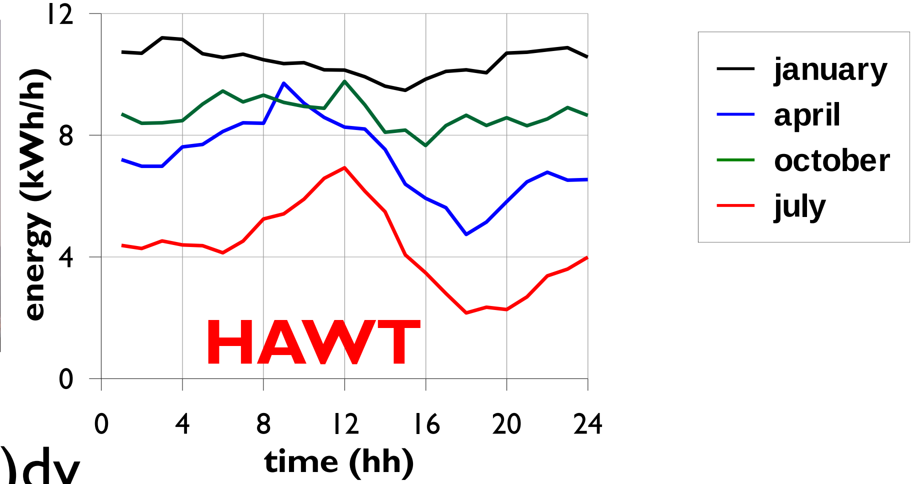
SMALL SIZE WTS: MIX PLANNING

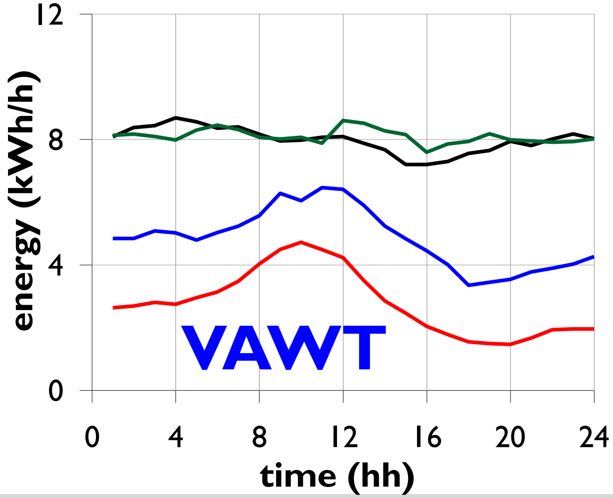
Hourly wind energy production - hour *h*, month *m*



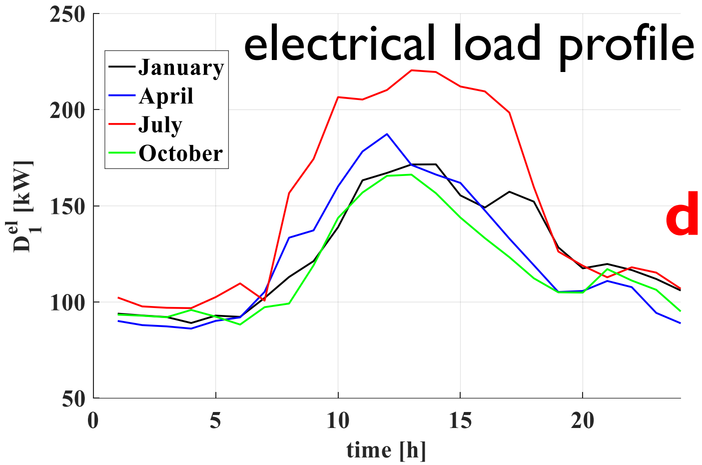


$$E=8760\int P(v)\times f_V(v)dv$$

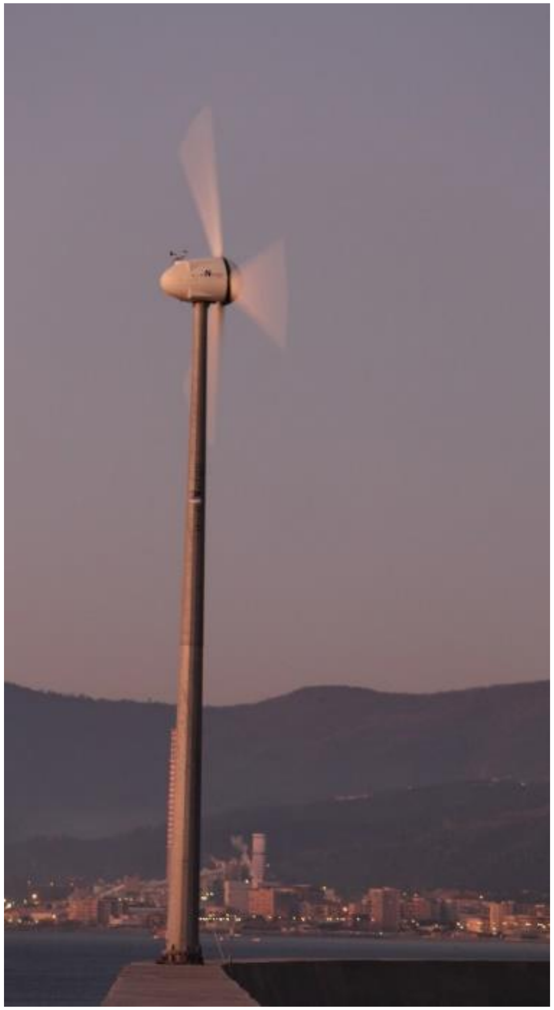




SMALL SIZE WTS: MIX PLANNING



As we can trust of declared power curve structural safety, maintainence?

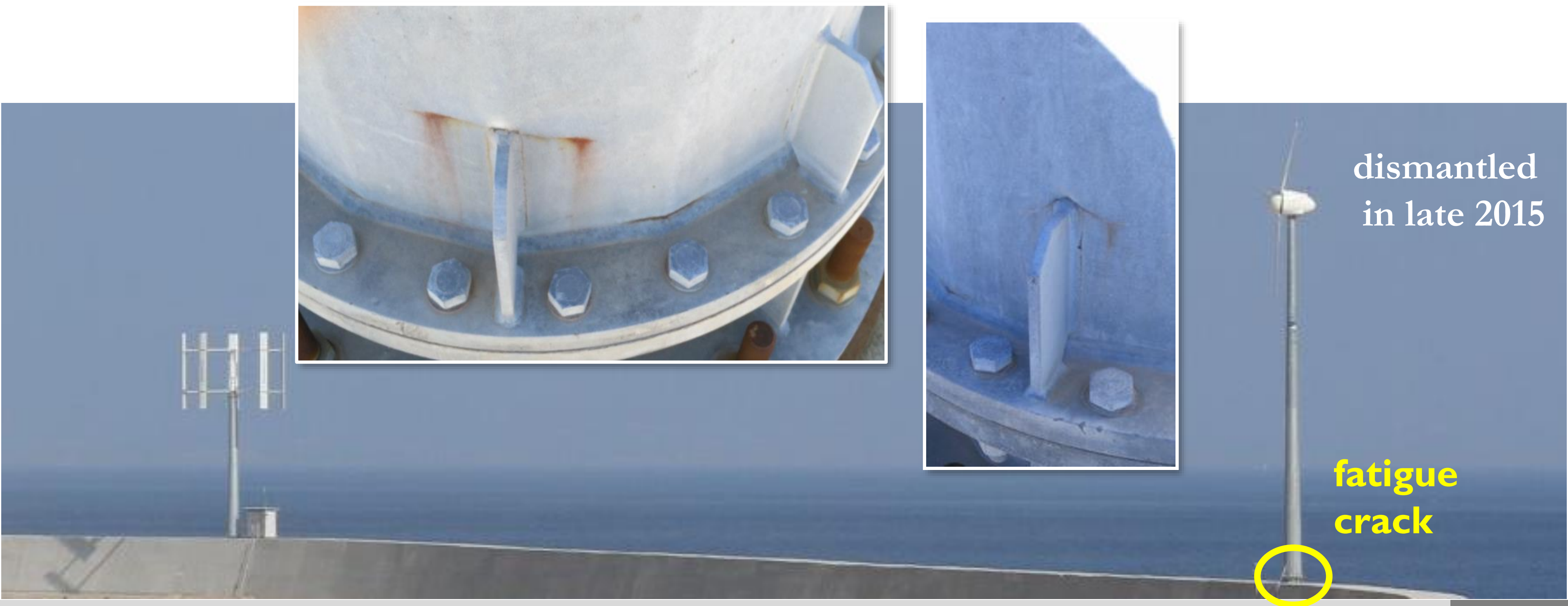


RESULTS	
HAWTs (n°)	3
PV[mq], tilt 0°	450
PV[mq], tilt 30°	0
C65microturbine (n°)	1
C30microturbine (n°)	0
Annual electricity from the grid [MWh]	572

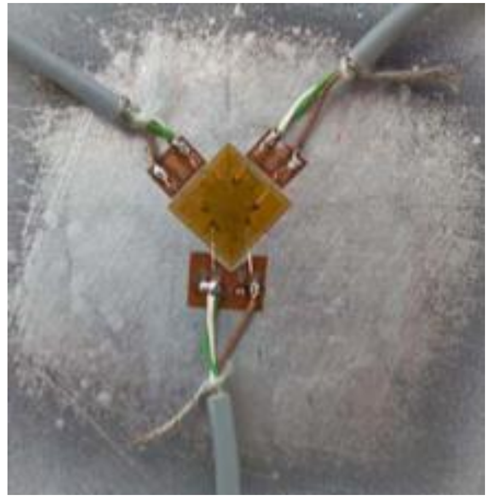
VAWTs (n°)	0

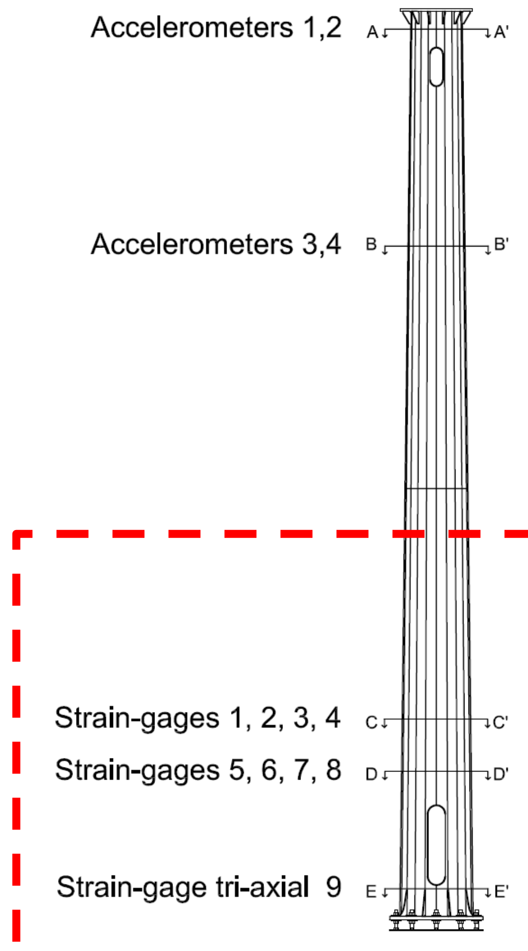
structural safety

- complex behavior, sensitive to turbulent and gusty wind
- low investments in research
- use of simplified design procedures



STRUCTURAL RESPONSE AND SAFETY



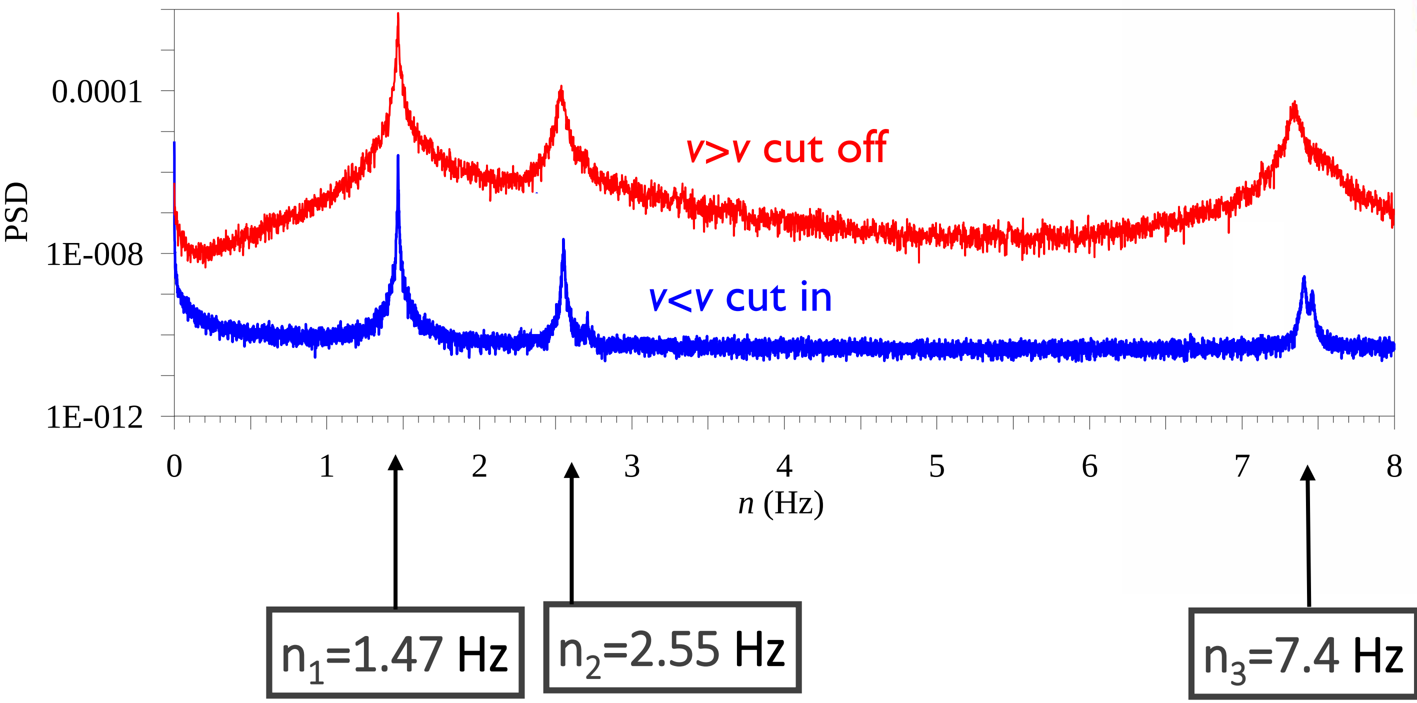


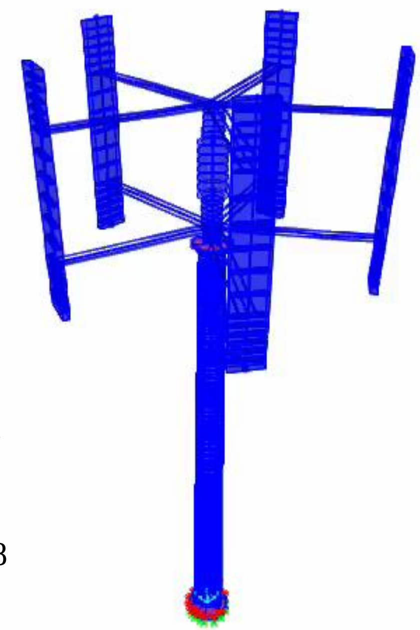
modal identification – parked turbine

Power spectral density function (PSDF) of the acceleration at top and of the strain at the base of the steel pole

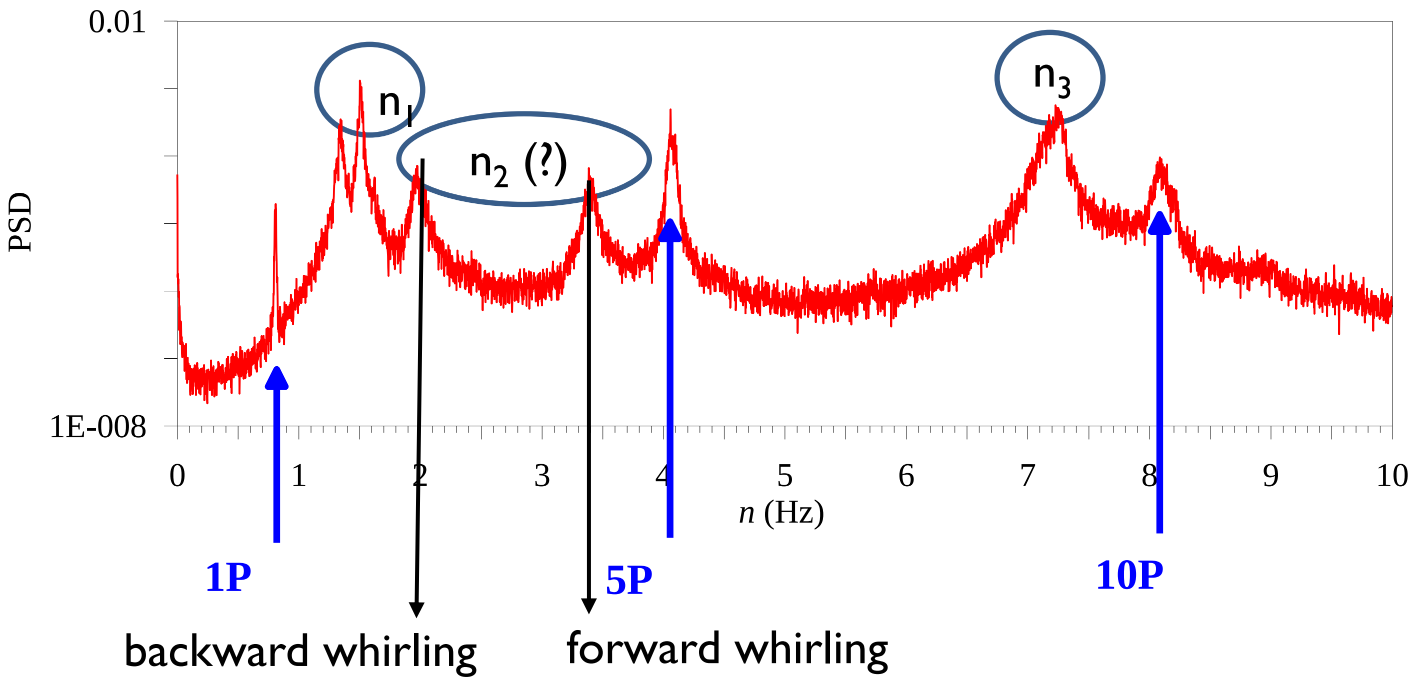
V= 18 m/s > cut off limit → rotation= 0 rpm (emergency stop)

V= 2 m/s < cut in limit → rotation= 0 rpm



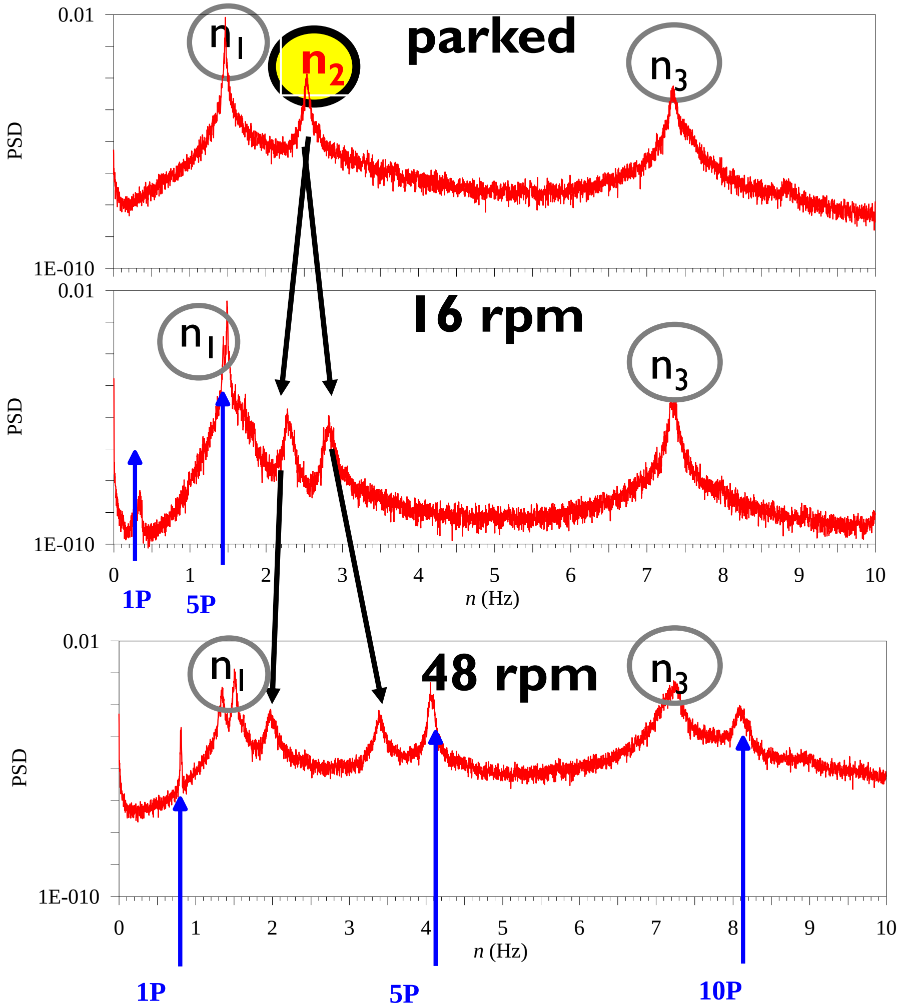


modal identification – rotating turbine



Harmonic loads occur at multiple of the rotor speed according to the number of the blades. Lines are labeled as 1P (one-per-revolution), 5P (five-per-revolution), 10P (ten-per-revolution)

STRUCTURAL RESPONSE AND SAFETY



ROTATION:

centrifugal forces result in a negative contribution to the stiffness matrix

tension helps stiffening the blade

spin speed of the rotor changes the natural frequencies

forward whirling mode increasing in frequency with rotor speed

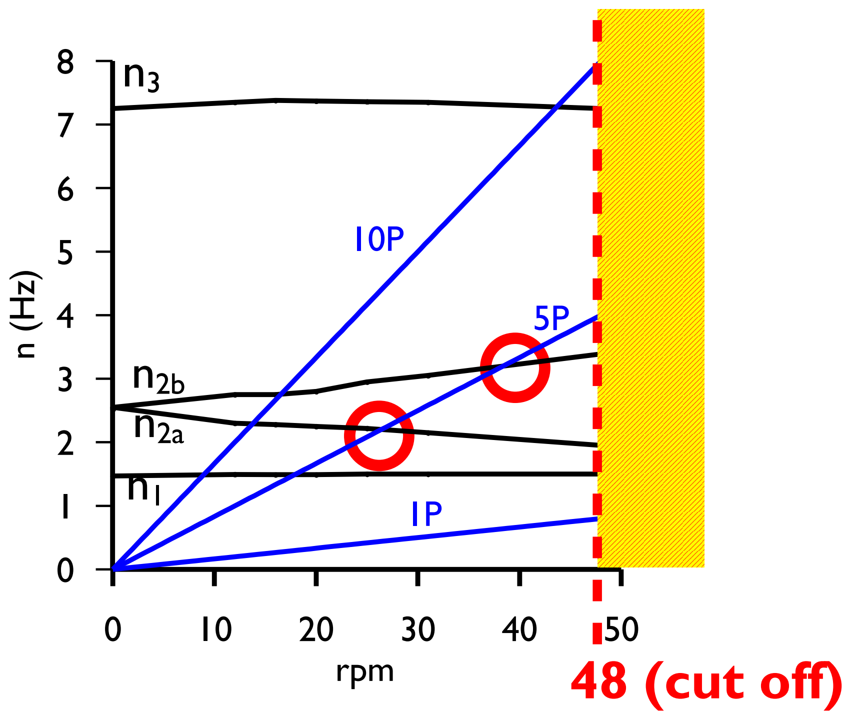
backward whirling mode decreasing in frequency with rotor speed

STRUCTURAL RESPONSE AND SAFETY

Structural response – first check

Campbell plot represents natural frequencies plotted against rotor speed

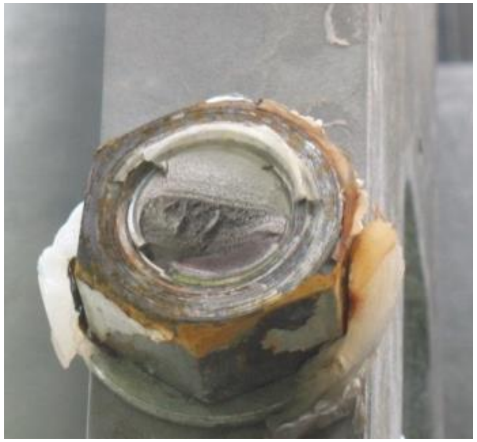
It is used as a diagnostic tool for understanding the interaction between rotor rotating speed and natural frequencies causing resonant conditions



STRUCTURAL RESPONSE AND SAFETY

Structural response

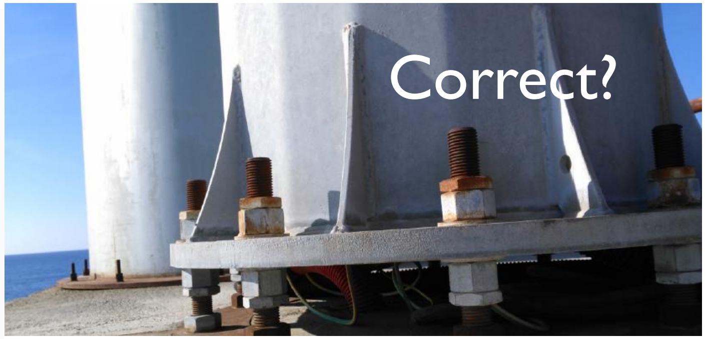
- these intersections have to be avoided
- fatigue damages have been experienced by turbines of similar typology in the connecting bolts between the blades and the support arms



STRUCTURAL RESPONSE AND SAFETY

HAWT
- ❑ Many out of service/repairs
- ❑ Fatigue cracks and dismantled in 2015

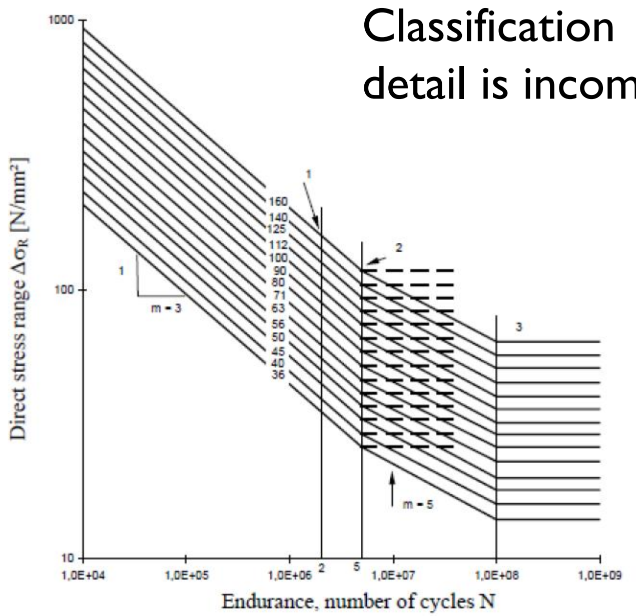
STRUCTURAL RESPONSE AND SAFETY

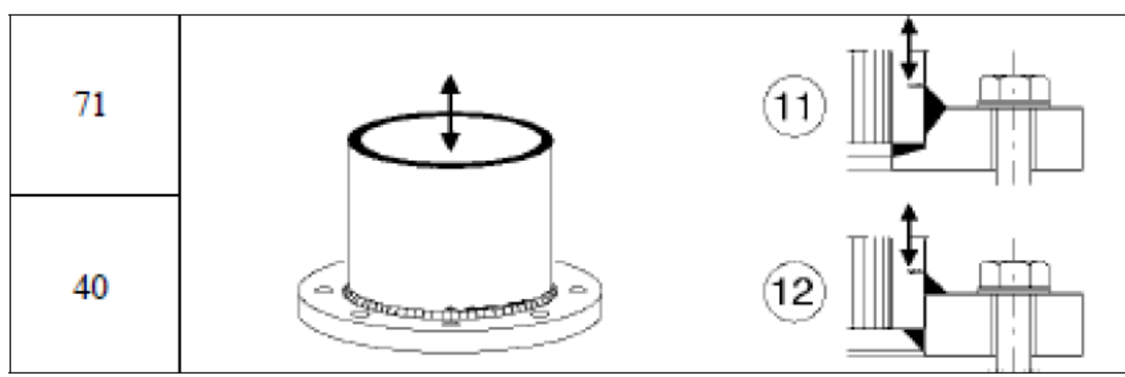


S–N curve approach is the basic method for fatigue strength evaluation of welded joints. The method is based on the design nominal stress, without taking into account explicitly the stress discontinuity due to the presence of the joint.

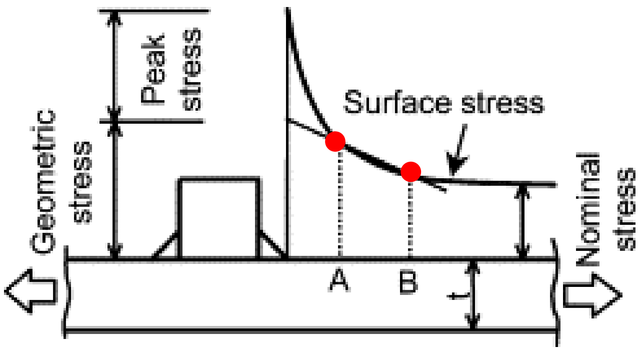
The geometry of the joint with its inherent stress distribution is taken into account by grouping joints with a similar behavior into a single fatigue class.

Classification method is simple to use, but difficult to apply if the object detail is incomparable to any classified joints



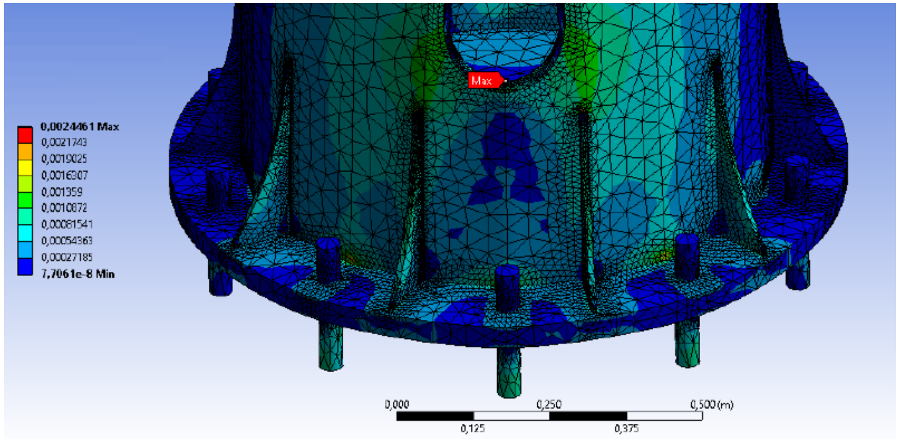


HOT SPOT approach



No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
1		Butt joint, special quality	See details 1) to 3) in table 8.3, for misalignement see note below.	112	45
2		Butt joint, standard quality	See detail 7) in table 8.3, for misalignement see note below.	100	40
3		Cruciform joint with full penetration K-butt welds	Weld toe angle ≤60°, for misalignement see note below.	100	40
4		Non load-carrying fillet welds	Weld toe angle ≤60°, for misalignment see note below	100	40

once we have created the hot spot model, stress in the detail for the fatigue analysis is obtained by a linear (or quadratic) interpolation using two points at a given distance from the welding



CONCLUSIONS

small size wind turbines in smart grids and smart cities

✓ **power curve.** *Which is the actual behavior and power production?*

Power curve are usually derived in aerodynamic wind tunnel in laminar smooth flow. Actually the behavior may be highly affected by gust and turbulence

Experience on two 20kW wind turbines

HAWT:

- It is realized with the same technology that it is used for the large ones, but the size and the overall weight of the machine is much lower
- The energy production of the is higher/Maintenance costs are higher
- It has been dismantled

VAWT:

- Technology is very simple; it is heavier, it does not need to rotate along the wind direction, it needs a less sophisticated control apparatus
- Turned out to be less exposed to gusts and fluctuations

CONCLUSIONS

small size wind turbines in smart grids and smart cities

✓ **power curve.** ***Which is the actual behavior and power production?***

Power curve are usually derived in aerodynamic wind tunnel in laminar smooth flow. Actually the behavior may be highly affected by gust and turbulence

✓ **optimal planning of the mix of power production units.**

Small size WTs competitive with other renewable sources? (e.g. PV solar)

By now PV solar seems more competitive. However, small size WTs are particularly suitable in isolated contexts, like small islands, and could be an appropriate technology to develop the strategic aim of small-scale distributed generation energy systems, as either complements or alternatives to centralized operations

✓ **structural response and safety:**

Their behavior is as much complex as the behavior of the large size turbines. Which are major shortcomings that may concern the structural safety?

Lightnings, turbulence, dynamic response, fatigue damages