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
OVERVIEW

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.

The lift force is largest for streamlined flow.

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

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.
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.
OVERVIEW

**Vertical Axis Wind Turbines (VAWTs)**

Savonius Rotor

*based on drag force*

Darreus Rotor

*based on lift force*

H-type Darreus
**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
<table>
<thead>
<tr>
<th>HAWT</th>
<th>VAWT</th>
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<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
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<tr>
<td>- Lower cut-in wind speed</td>
<td>- no yaw mechanism</td>
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<tr>
<td>- Higher efficiency</td>
<td>- no pitch regulation</td>
</tr>
<tr>
<td>- Lower cost /power</td>
<td>- few movable parts → lower maintenance costs</td>
</tr>
<tr>
<td>- Ability to furl rotor out of wind</td>
<td>- low rotating speed → produce low noise</td>
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<table>
<thead>
<tr>
<th><strong>Disadvantages</strong></th>
<th><strong>Disadvantages</strong></th>
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<tbody>
<tr>
<td>- Active yaw drive</td>
<td>- Low wind speed</td>
</tr>
<tr>
<td>- Difficult maintenance</td>
<td>- Low efficiency</td>
</tr>
<tr>
<td>- Many moving parts</td>
<td>- Difficult over speed control</td>
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<tr>
<td></td>
<td>- Difficult starting</td>
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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?
**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.
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)
We can evaluate the energy production by combining the power curve with the histogram of the wind data.

\[
E = \sum n_i P(v_i) \Delta t
\]

\[ [kW \times 10\text{ min}] \]

\[
E = \sum n_i P(v_i) \Delta t / 6
\]

\[ [kWh] \]
• 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: $E_{\text{year}}$

\[ E = N_0 \int_0^\infty P(v) \cdot f(v) \cdot dv \]

- $P(v)$: power curve function \([\text{kW}]\)
- $f(v)$: wind distribution function
- $V_{\text{start}}$: cut-in wind speed
- $V_{\text{stop}}$: cut-out wind speed
- $N_0 = 8765$ hours/year
Two small size wind turbines
20 kW HAWT
20 kW VAWT (de-rated)

installed in 2012
renewed in 2014

swept area 79m$^2$

POWER CURVE

experimental activity with Port Authority of Savona

18m

swept area 45m$^2$
power to net and blade rotation speed monitoring
power, rpm, wind speed (cup anemometer), direction
integrated power control system – sampling rate: 0.1 Hz
wind monitoring

cup anemometer
sampling rate: 0.1 Hz

sonic anemometer
sampling rate: 10 Hz
POWER CURVE

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
3° step: Transferring wind to the turbine

roughness model of the surroundings (ESDU)

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

\[ v_{\text{VAWT}}(\alpha) = k_v(\alpha) \times v_s(\alpha) \]
\[ v_{\text{HAWT}}(\alpha) = k_h(\alpha) \times v_s(\alpha) \]
This is a mistake one can still find in the field of small turbines.

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**Figure:**
- **Left:** Turbulence intensity map with different color ranges indicating intensity levels.
- **Center:** Graph showing experimental power curve of small-size wind turbines for land and sea environments. The graph includes data for different turbulence intensity levels: $I_u < 10\%$, $I_u < 20\%$, $I_u < 40\%$.
- **Right:** Graph showing power output $P$ vs. wind velocity $v_{10}$ for different turbulence intensity levels.

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**Caption:**
- **LAND** and **SEA** labels indicating the environment for the experiments.
- **by land** and **by sea** labels indicating the experimental conditions.

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**Legend:**
- Blue: $<=0.1$
- Yellow: $>0.1 - 0.2$
- Green: $>0.2 - 0.3$
- Red: $>0.3$
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.

POWER CURVE
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.
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### POWER CURVE

\[
E = 8760 \int_0^\infty P(v) \cdot f(v) \cdot dv
\]

**VAWT (2016)**
- produced: 8 MWh
- expected: 15 MWh

**HAWT (2014)**
- produced: 11 MWh
- expected: 24 MWh

many out of use - dismantled in 2015
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

control room  concentrated solar power  gas turbine

plug-in electrical vehicles  PV units  chiller: waste heat into cooling energy  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**

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.

**optimal planning**
including small size Wind Turbines

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20kW 20kW
SMALL SIZE WTS: MIX PLANNING

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

$S_{PV}^{s,\alpha}$ [m$^2$]: surface covered by PV panels with tilt $\alpha$;

$n_{s}^{w}$: number of WTs

$C_{CHP}^{s,y,m,t}$: number of micro-turbines

costs and benefits of the grid

$C_{Grid}^{s,y,m,t} = C_{s,y,m,t}^{el} E_{s,y,m,t}^{IN} - b_{s,y,m,t}^{el} E_{s,y,m,t}^{OUT}$

- cost power purchased from the grid
- benefit power sold to the grid

Maintenance
SMALL SIZE WTS: MIX PLANNING

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

Installation costs:
\[
\min \left\{ K + \sum_{y=1}^{Y} \frac{C_y}{(1+i)^y} \right\}
\]

Annual discounted operating costs

PV surface installed in site s inclined \( \alpha \)

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

Number of microturbines (CHP) of kind \( \beta \) in site s

Number of wind turbines in site s

Unit costs

Number of days in month \( m \)

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

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

- January
- April
- October
- July

**hourly power generated - PV**

- Tilt angle 0°
- Azimuth 180°

TU 1304 | WINERCOST | Napoli (Italy), 23-28 April 2017
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SMALL SIZE WTS: MIX PLANNING

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

$$E = \int_0^{24} P(v) \times f_v(v) dv$$

- **HAWT**
- **VAWT**

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

**RESULTS**

<p>| | |</p>
<table>
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<tbody>
<tr>
<td>HAWTs (n°)</td>
<td>3</td>
</tr>
<tr>
<td>PV[mq], tilt 0°</td>
<td>450</td>
</tr>
<tr>
<td>PV[mq], tilt 30°</td>
<td>0</td>
</tr>
<tr>
<td>C65 microturbine (n°)</td>
<td>1</td>
</tr>
<tr>
<td>C30 microturbine (n°)</td>
<td>0</td>
</tr>
<tr>
<td>Annual electricity from the grid [MWh]</td>
<td>572</td>
</tr>
</tbody>
</table>
STRUCTURAL RESPONSE AND SAFETY

structural safety

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

fatigue crack

dismantled in late 2015
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

- $V = 18 \text{ m/s} > \text{cut off limit} \rightarrow \text{rotation} = 0 \text{ rpm (emergency stop)}$
- $V = 2 \text{ m/s} < \text{cut in limit} \rightarrow \text{rotation} = 0 \text{ rpm}$

$\text{PSD}$

$n_1 = 1.47 \text{ Hz}$  
$n_2 = 2.55 \text{ Hz}$  
$n_3 = 7.4 \text{ Hz}$
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 – 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.

![Campbell plot](image)
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.
HAWT
- Many out of service/repairs
- Fatigue cracks and dismantled in 2015
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

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