This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 792059

Oct. 28th

PV Tracker – Design and Control

INTRODUCTION

(10:00-12:00)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

PV TRACKER – DESIGN & CONTROL - *Convert Italia -*

General Topics	*Speaker*	*Time*
Introduction to Tracker Device for PV plant. Mono axial tracker Concept Design: performances vs reliability	***G. Demofonti***	***10 min***
Structural Design of mono axial tracker	*A. Ricci*	*20 min*
Structural Design of mono axial tracker: Wind Loads and Aerodynamic design	*A. Ricci*	*20 min*
Questions & Answers	**All**	***10 min***
Criteria for the evaluation of corrosion resistant of tracker operating in aggressive environment	*G. Demofonti*	*20 min*
Electronic control board and powering system of mono axial tracker	*A. Timidei*	*15 min*
Failure modes, Qualification of tracker and Maintenance actions	*G. Demofonti*	*15 min*
Questions & Answers	**All**	***10 min***

Introduction to Tracker Device for PV plant.
Performances/Reliability *Vs* LOCE

Specific Topics:

1. Introduction to Tracker System for PV plant
2. Basic performances and reliability required to a single-axis tracker in relation to service conditions, environments and expected life of the PV plant.
3. Presentation of solutions developed in GOPV project

Speaker:

Giuseppe Demofonti, *Convert Italia*

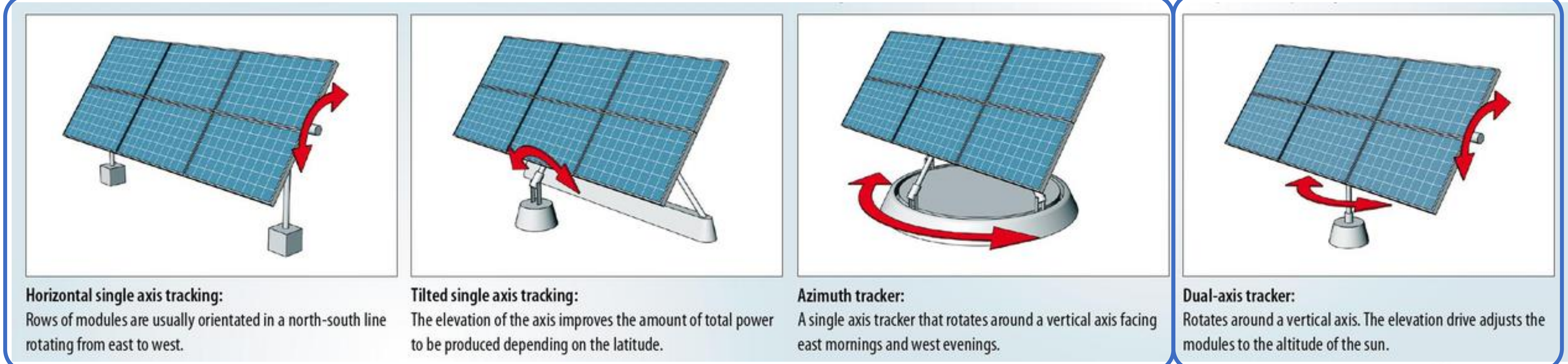
Time: 10 minutes

Introduction to Tracker Device for PV plant.

TRACKER

- The productivity of PV modules depends, in general, on their **inclination** with respect to the sun.
- From the beginning of PV technology, many efforts have been spent to develop devices able to **change the orientation** of the module surface.
- **Single or double axis trackers** have been developed instead of fixed oriented structures.

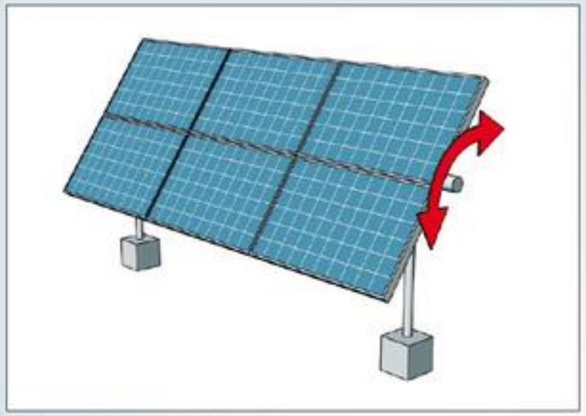
Concentrated Photovoltaics panel



Standard Photovoltaics panel

Introduction to Tracker Device for PV plant.

Horizontal single axis tracker



Horizontal single axis tracking:
Rows of modules are usually orientated in a north-south line rotating from east to west.

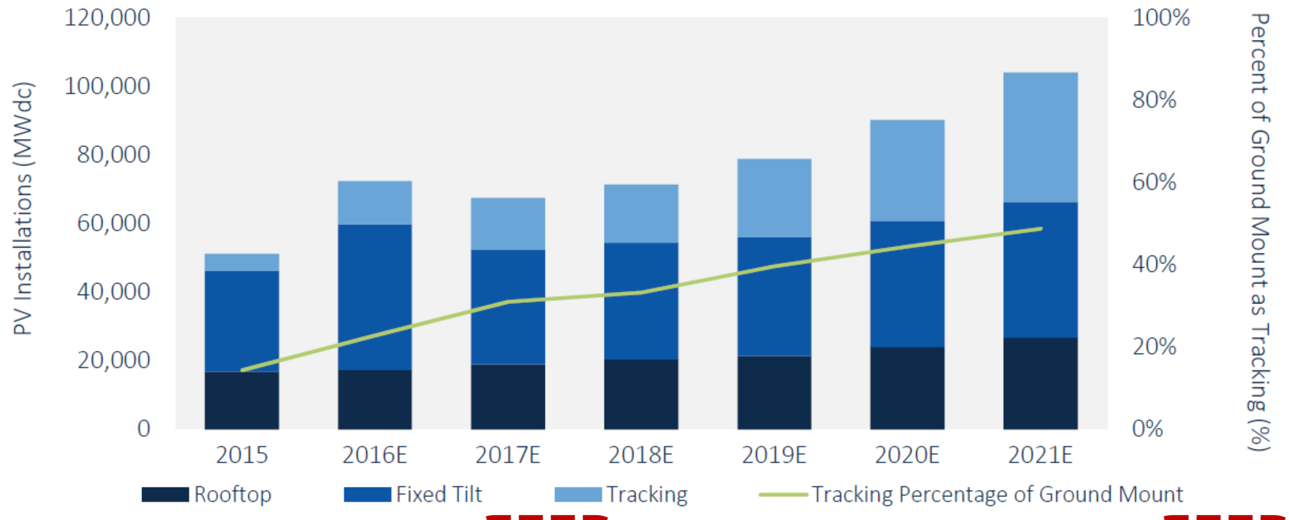
Single axial tracker in large PV utility plants

SINGLE AXIS TRACKER

- The costs/benefits balance in large PV plants of standard PV modules identified the **horizontal single axis tracker as best compromise**: with a reasonable increase of CAPEX and OPEX costs, it allows to **increase productivity by 20-30%.**

- This potential is driving a growing interest for PV horizontal single axis trackers with strong and fast increase in market share over the coming years: **more of 50% of market in 2021**

Global PV Mounting Systems Forecasts, 2015-2021E (MWdc)

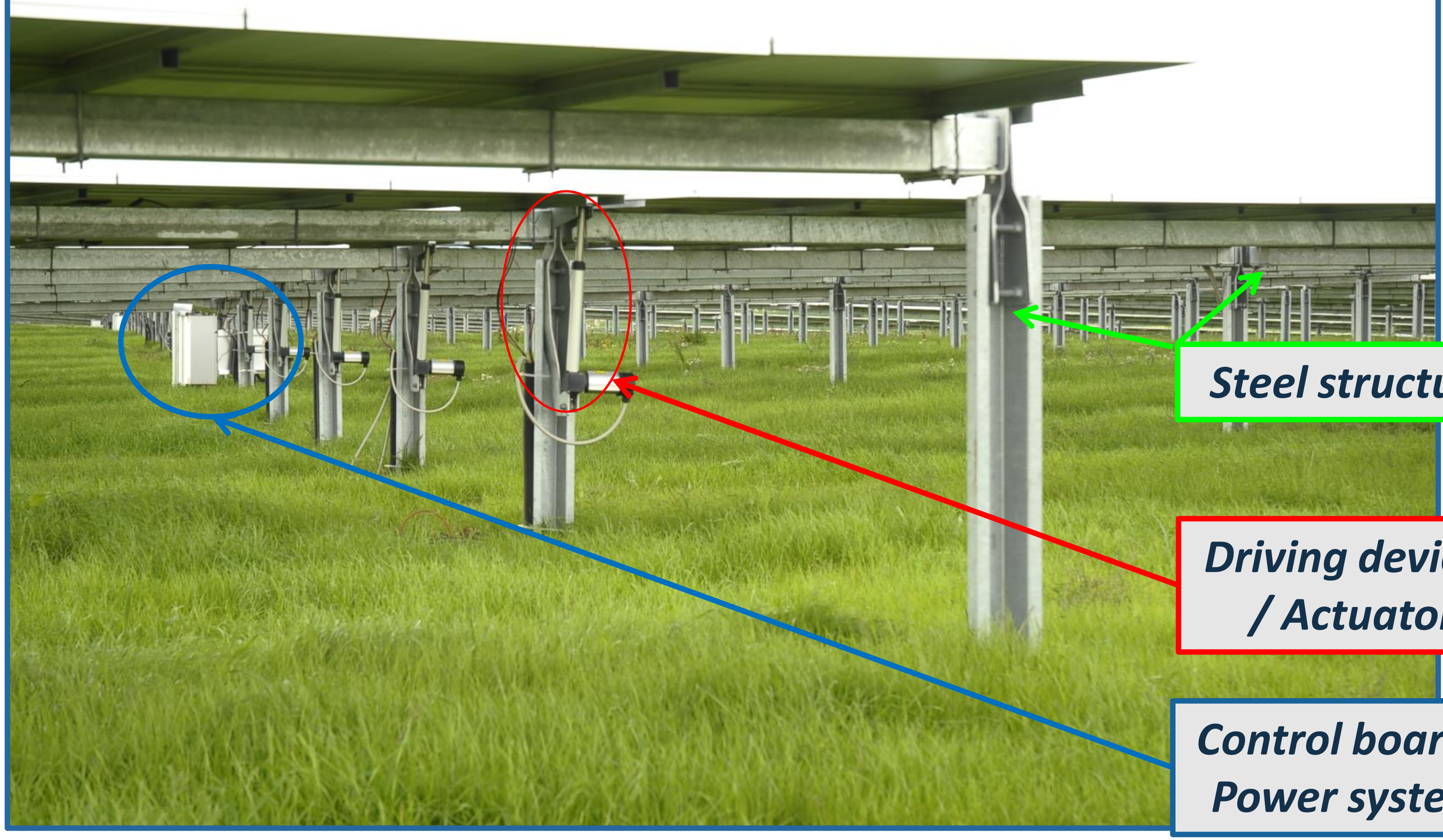


Global Racking Type Forecast (MWdc)	2015	2016E	2017E	2018E	2019E	2020E	2021E
Fixed Tilt*	29,352	42,429	33,451	34,007	34,634	36,759	39,568
Tracking*	4,975	12,631	15,078	17,000	22,808	29,419	37,747
Total	51,230	72,412	67,487	71,411	78,895	90,216	104,087
Tracking Percentage of Ground Mount	14%	23%	31%	33%	40%	44%	49%

Source: GTM Research *Fixed tilt includes utility ground mount, commercial ground mount, and canopies; Rooftop includes both pitched and flat roofs

Horizontal single axis tracker.

Key tracker components



Steel structure

Driving devices / Actuator

Control board / Power system

Technical requirements for horizontal single axis tracker

Good reliability in relation to the hazards from the environment

vs

Low LCOE

Hazards from the environment :

- **External loads**: wind, snow,….
- **Ground movements**: landslide, earthquake, ….
- **Weather events**: lightning strikes, storms,….
- **Time:** aging, gear wear of driving devices, …
- **Aggressive environment**: corrosion,….

Appropriate Design:

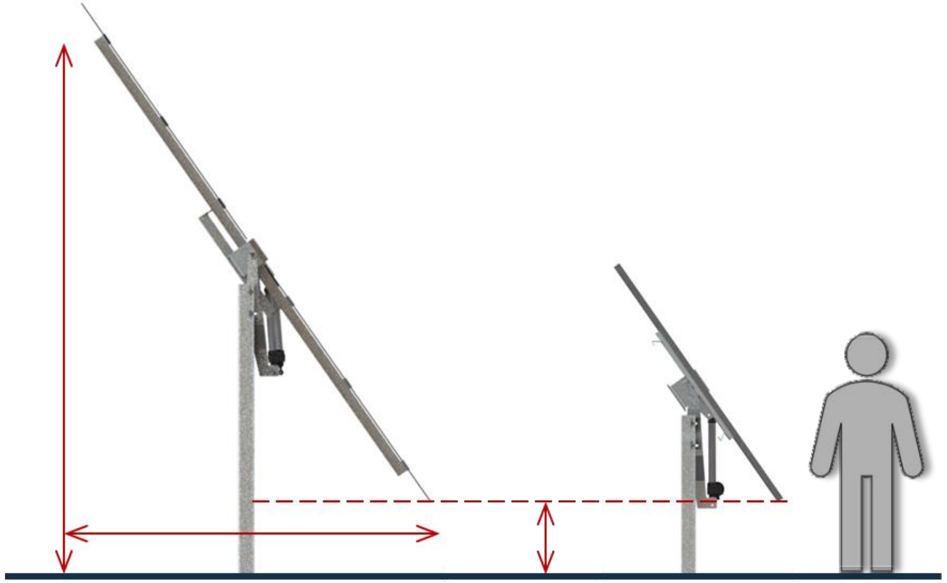
- **Use of consolidate knowhow** about the steel structure design;
- **Use of available international standard** and certification codes,
- **Accurate models for loads- tracker interaction**:
  - Computational Fluid Dynamics (CFD) Analysis
  - Finite element stress-strain analysis of tracker steel critical components.
- **Full and Mid-scale lab test:**
  - Wind-tunnel test
  - Tests in climatic chambers on electronic /electromechanical components,
- **Appropriate use of available field experiences**

Horizontal single axis tracker for bifacial modules

The new horizontal single axis tracker for bifacial modules should **ensure a significant contribution of reflected light** on the back of the PV module.

A new architecture of the tracker is needed: from single module to double module in portrait configuration

The **overall height of the tracker is more than doubled**, with consequent **greater effect of external loads** on the stability of the tracker, in particular wind loads.



GOPV project: Goals concerning Tracker Device

AIMS

Reduction of the Levelized Cost Of Electricity LCOE by:

- Contribution for **increasing the yearly producible at the string level up to 2430 kWh/kWp:**

  New tracker design and tracking strategy focused on the use of **bifacial modules**

- Decreasing **tracker cost down to 0,11€/W:**

  Use of **lower cost structure materials/coiting:** Weathering steel or Glass Fiber Reinforced Polymer instead of HDG steel or Sendzimir galvanized steel

- Extending **service lifetime** of the tracker up to **35 years:**

  Improving existing know how for **correctly predict the corrosion behavior and aging** of Weathering steel in specific environment

FINAL OUTPUT

A **pre-series of new tracker solutions** will be available for

*"**Integrated PV System Demonstration**"*

GOPV Tracker Main Features

CONCEPT DESIGN

TRACKER CONFIGURATION

- ✓ 2 modules portrait
- ✓ Total number of modules: 26
- ✓ Dimension: ≈ 4 m x 14 m
- ✓ Tracking angle: ± 55°

POSSIBLE EVOLUTIONS

- ✓ Connection of two adjacent trackers
- ✓ Overall dimensions: ≈ 4 m x 28 m

ELECTRONICS

- ✓ Improve Wired Communication Control Board and Drive to reduce the length of cables
- ✓ Develop a “new” Tracker Wireless Control System: SCADA 2° level
- ✓ Improve a Self-Power System to supply locally and independently groups of trackers

PV TRACKER – DESIGN & CONTROL
Convert Italia

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PV Tracker – Design and Control

STRUCTURAL DESIGN

(10:00-12:00)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

Structural Design of Mono Axial Tracker

Specific Topics:

1. Design Inputs – Approaches - Restrictions
2. Main Codes
3. GOPV project: Goals concerning Tracker Design

Speaker:

Andrea Ricci, Convert

Time: 20 minutes

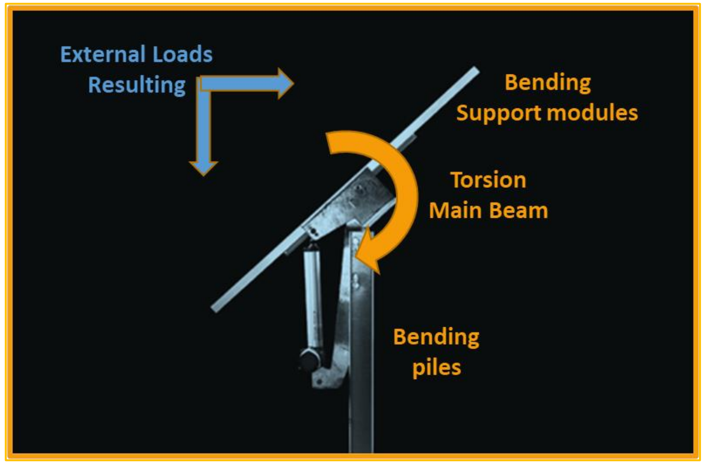
Design Input and Approaches

Permanent Loads

1. Structure weight (≈40% of total masses),
2. Modules weight (≈60% of total masses).

Variable Loads

1. Snow Load,
2. **Wind Load** *(Static pressure and dynamic effect),*
3. Thermal Load,
4. Seismic Load.



→ Except for particular cases, in common applications **Wind Loads govern the tracker design**.

Design General Restrictions

General Consideration

Trackers have to be considered as **common steel structures** and be compliant with civil regulations such for example EN1993 – Eurocode 3.

- ➢ Main structures calculation requirement in terms of deformations and resistance have to be respected.

Main resistance and deflection evaluation

All components must be adequately designed to avoid local instability problems (local buckling)

- ✓ Bending and Torsional section resistance and deflection for the **main beam** (tube),
- ✓ Bending section resistance and deflection for module **rails**,
- ✓ Bending and twisting section resistance for the **piles**.

Design Specific Restrictions

Aiming error

In all service ranges no plastic deformations are permitted:

- Tracking accuracy must be guaranteed in the range of a few degrees (usually around 1° or 2°) of error throughout the expected life of the project

Module Deflection

- PV-Modules have to be considered as independent elements, which do not produce any structural resistance improvement and which may have their own rotations/displacements.
- Commonly it is considered the ***L/150 limit*** as a deflection restriction prescribe to prevent failures among the connection's points (bolts, rivet, clamps, etc).

Large Scale application

The most restrictive requirement is the "large scale application":

- High range of possible installations
- Cost reduction purpose → steel reduction as much as possible.

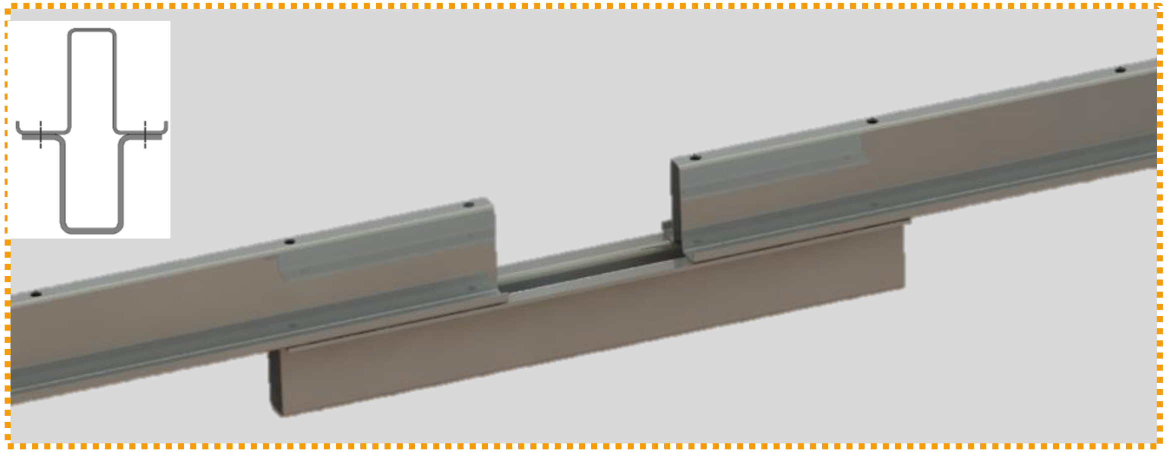
Standard Design - Piles

- Piles are one of the most variable elements in tracker designing, since it is affected by all soil-mechanical-characteristics possible changings.
- Currently more and more detailed models for embedded length calculation are requested and eventually confirmed with pull-out tests.
- This is turning out to be a consolidated practice given the uncertainty about the soil properties definition on large sites.
- Omega (Ω) sections maximize the contact surface with the soil, reducing embedment lengths.
- Concrete foundations in general are not used.

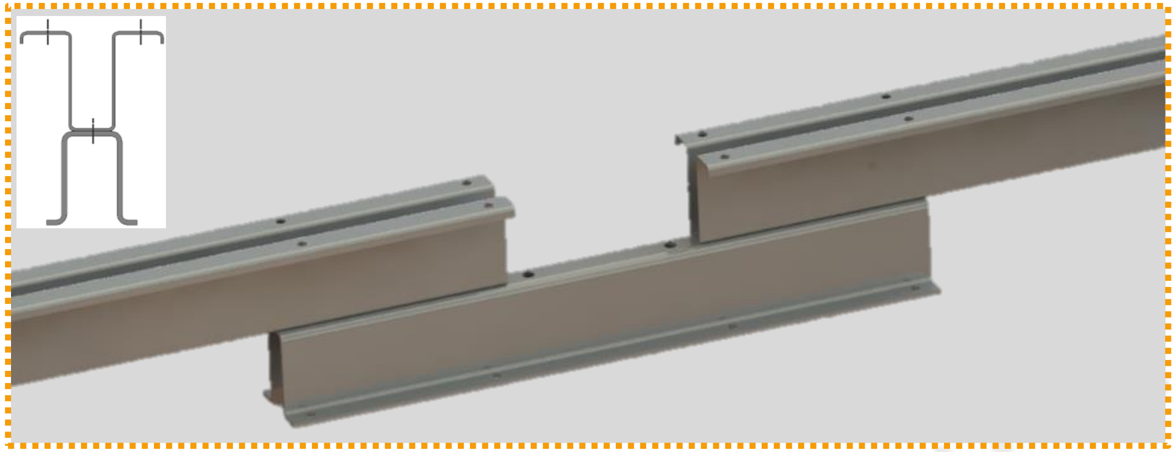
Standard Design – Standardization process

- One of the main standard components scope is to be **easily manufactured** worldwide and **easily adaptable** to different situations.
- As for example, the module rails have been developed to be suitable in both configurations: frame and frameless module installation (currently both available in the market).

Frameless configuration *(GOPV Project)*



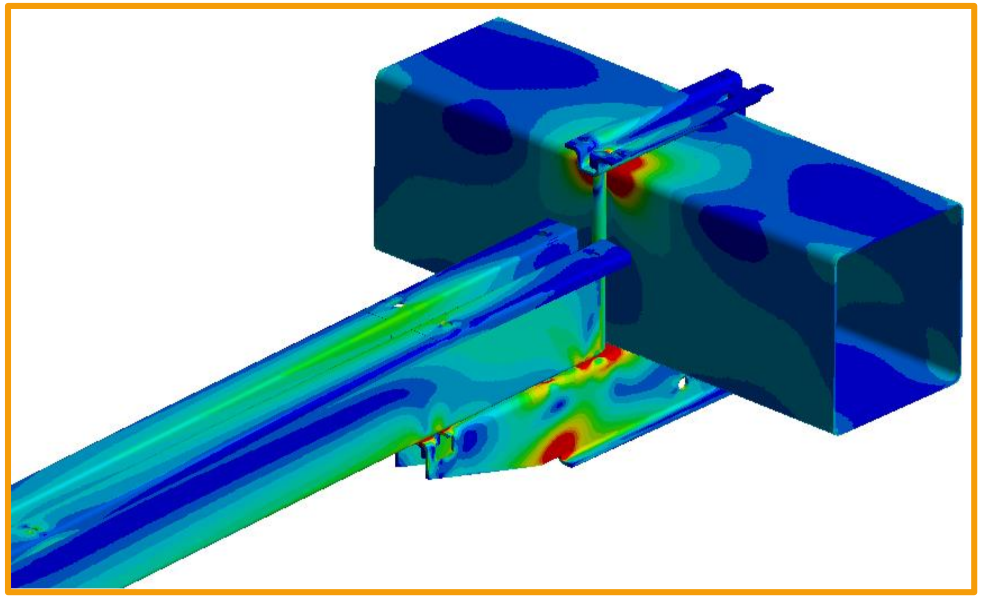
With frame configuration



→ *Same omega shape profiles for both configurations*

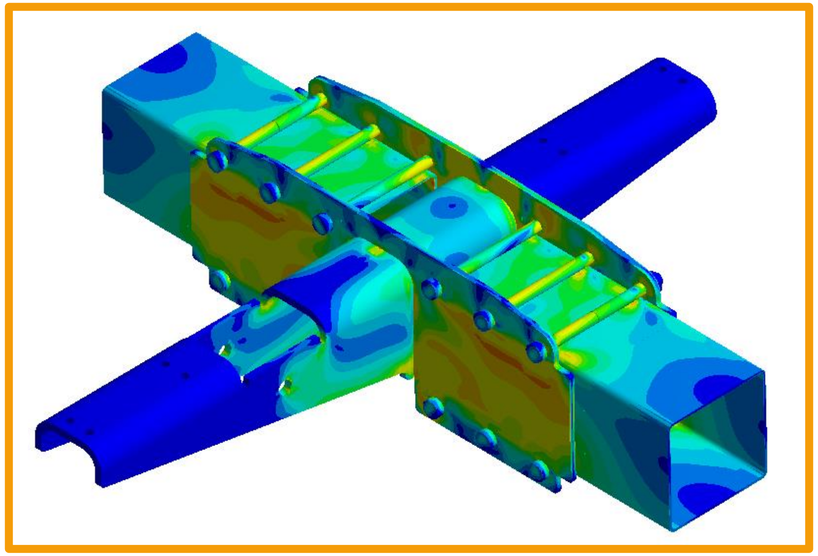
Connection Design

- Most of connections are bolted joint, assembled directly in field, whereas welds are realized only into manufacturing workshop and on small single tracker components *(mainly mechanical components)*.
- Due to their complexity (geometrical and in terms of loading condition), many times finite element analysis and lab testing are required to make reliable calculation and a cost-effective design.



Mechanical Elements (KIT) Design

- All mechanical elements (KIT) needs a specific design, mainly based on:
  - ✓ the load inputs coming from standard component design (defined by the codes),
  - ✓ Installation and maintenance requirements
  - ✓ Movement and mechanical performances granted along the project life.
- Due to their complexity (geometrical and in terms of loading condition), many times finite element analysis and lab testing are required to make reliable calculation and a cost-effective design.



Structural Calculation Report

Since trackers are considered as civil structures, in general a *Structural Calculation Report* of tacker for each PV plant must be carried out .

Structural Calculation Report Index:

- General description of PV plant
- Standard rules and codes used
- Mechanical properties of used steel
- Analysis of Loads: permanent and variable
- Loads combination
- Structural FE analysis
- Design of mechanical connection
- Pull-out of piles analysis and geotechnical assessment

Available Codes

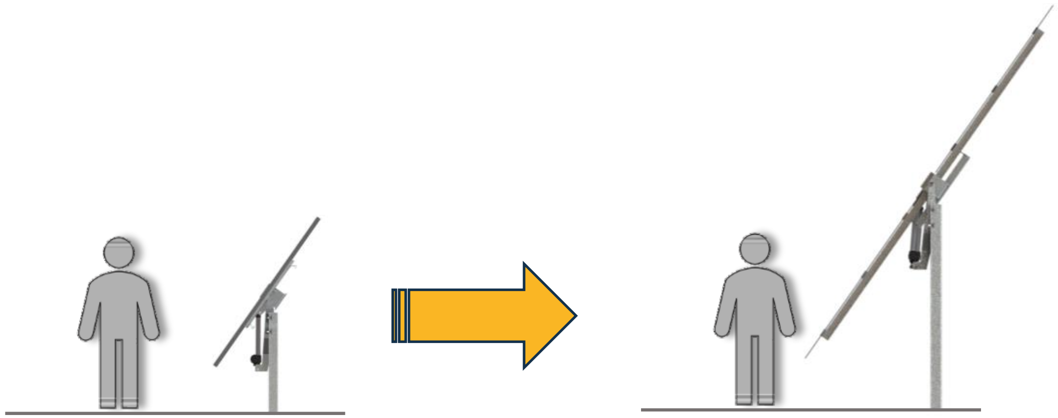
General overview

- A **dedicated design code** focused on tracker don't exist.
- Two main international standards approaches exist dedicated to steel structure and building:
  - ✓ **Eurocode**
  - ✓ **ASCE 7-16**
- In both code "physics described" always remains the same, they difference, in terms of:
  - ✓ loads and load combinations,
  - ✓ return time of each characteristic variables loads (**50 years vs hundreds of years**),
  - ✓ difference between the "Service Limits" and "Ultimate Limits".

- Tracker must be designed according to the local regulations, since trackers are considered as civil structures.
- Additional requirements coming from the customer must be meet.

- Assumptions **too conservative** could make a project **no-economically favourable:** generally studies to derogate single standard aspects must be made.
- *A comprehensive regulation focus on monoaxial tracker is being developed in the **IEC–WG9**: at the moment, it is only focused on people safety.*

GOPV project: Goals concerning Tracker Design



Main issues 1P → 2P

CRITICAL ASPECTS

- ✓ NEW appropriate Design,
- ✓ Improvement of wind load evaluation criteria
- ✓ Higher loads on the actuator/motor device

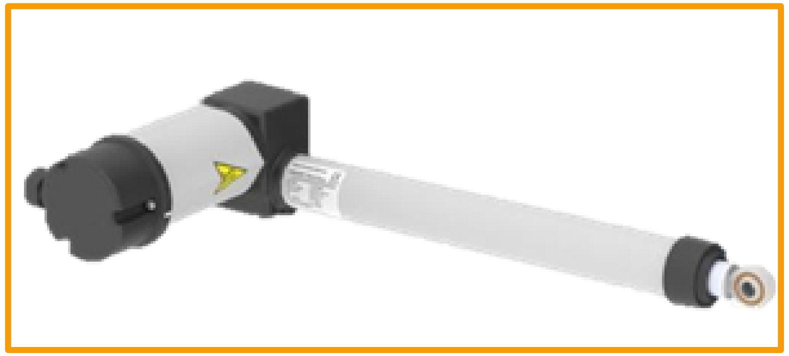
NEEDS

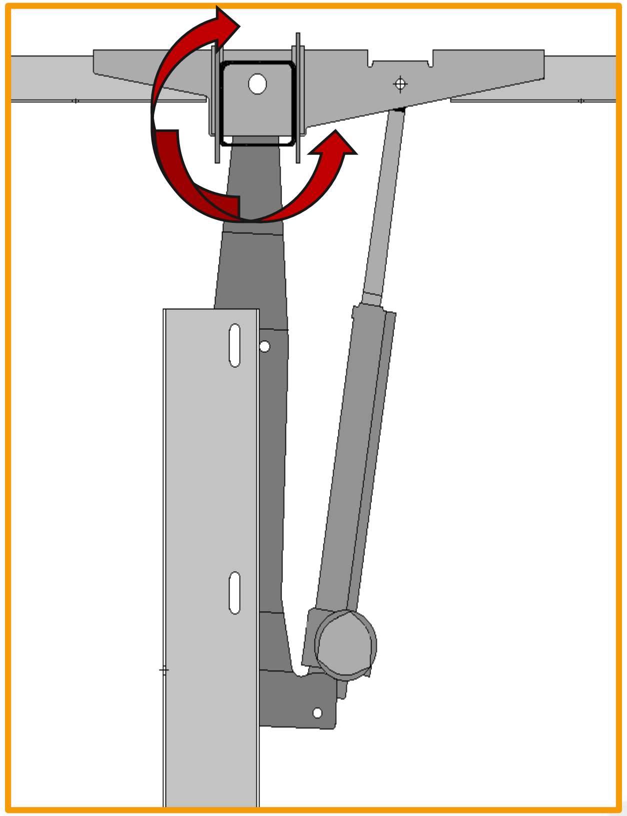
- ✓ More accurate models for wind loads: Wind tunnel tests and CFD simulation.
- ✓ Development of a more performing actuator.

Actuator – Motor device

Increasing tracker dimensions the motor system needs to be improved to stand higher loads.

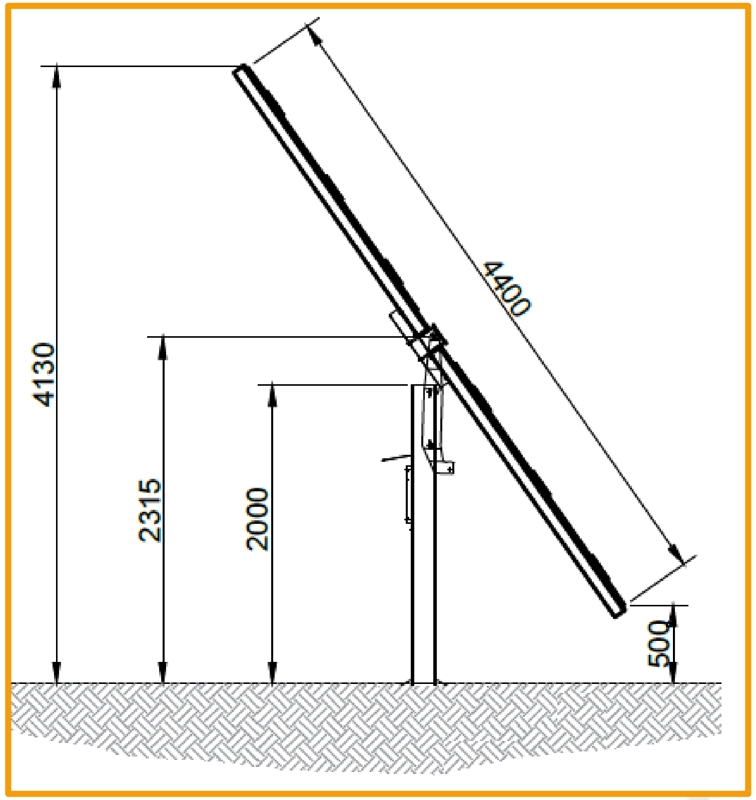
	Previous Actuator	Current Actuator	New Targets
Maximum Load	**45,0** kN	**60,0** kN	**90 - 110** kN
Maximum Displacement	370 mm	420 mm	800mm





Design Input – GOPV 2-P Tracker

- Configuration: **2 PV modules portrait**,
- Number of **modules: 26** *(dimension of module ~ 2000 x 1000 mm)*
- Modules Installation: **frameless**, **installed by 3 clamps for side.**
- The maximum tracking will be **±55°**, with an error of ±2°.
- The minimum distance from the ground is: **0.50 m**
- **An actuator** for each tracker.



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goPV

Oct. 28th

PV Tracker – Design and Control

WIND LOADS and AERODYNAMIC DESIGN

(10:00-12:00)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

Structural Design of Mono Axial Tracker:
Wind Loads and Aerodynamic Design

Specific Topics:

1. Wind loads *Base Knowledge*
2. Wind Loads: *Main Codes approach*
3. Wind loads evaluation: *technical needs & available approaches*
4. Wind Loads and Aerodynamic Design: *GOPV Project*
   - ✓ Wind tunnel – Static tests & Aeroelastic tests
   - ✓ CFD Simulations / Analysis

Speaker:

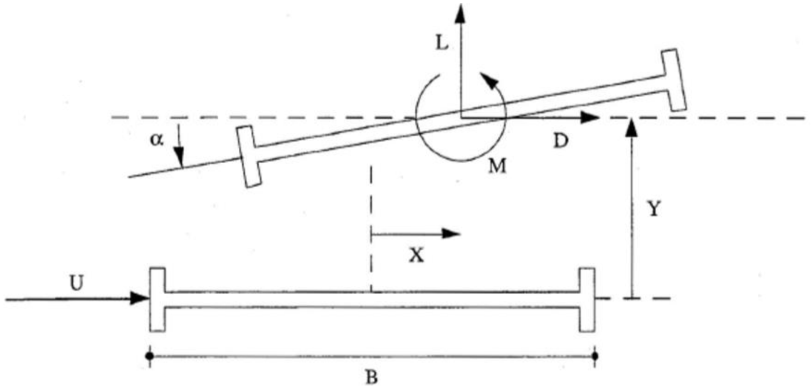
Andrea Ricci, Convert

Time: 20 minutes

Wind Loads: *Base Knowledge*

Aerodynamic actions on structure put in a uniform wind flow:

- ✓ **Drag (D)**, acting along the direction of flow,
- ✓ **Lift (L)**, acting perpendicular to the flow direction,
- ✓ **Torsional Moment (M)**, acting around tracker axis.



Drag **D** and Lift **L** forces are **defined as function** of the airflow velocity and surface width:

$$c \cdot {}^{1}/_{2}\, \rho v^2 \cdot B,$$

*where **c** represents a coefficient obtained for several angle of attack **α** in wind tunnel tests;*

Drag **D** and Lift **L** forces can be considered **simultaneously** determining force ***F***, perpendicularly to the surface:

$$F = c_p \cdot {}^{1}/_{2}\, \rho v^2 \cdot B,$$

Where c_p is the "wind pressure coefficient" which changes as a function of the attack angle α.

Wind Loads: *Main Codes approach*

Definition of wind velocity to use in the design

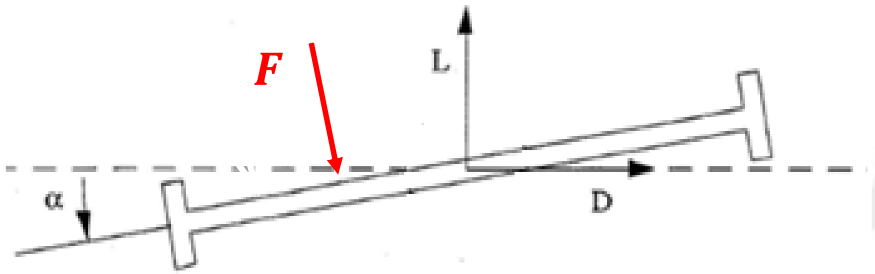
Two main wind approaches coexist:

- ✓ "***mean wind velocity***" 10 minutes average wind speed - represents by Eurocode 1-4,
- ✓ "***gust wind speed***" 3 second gust wind speed - represents by the ASCE 7-16

Describing the **same phenomenon** both approaches depend mainly by the **same parameters** (such as terrain topography, roughness,…) and lead both to the calculation of the **Peak Pressure**.

Loads resulting force

- The two codes differ on the force ***F*** application point:
  - ✓ in the Eurocode 1-4 is put fixed at L/4 from the panel edge,
  - ✓ in the ASCE 7-16 it is variable proportionally to wind coefficients.
- The equivalent torsion moment ***M*** acting to the main beam, would be higher when considering the Eurocode 1-4 approach.

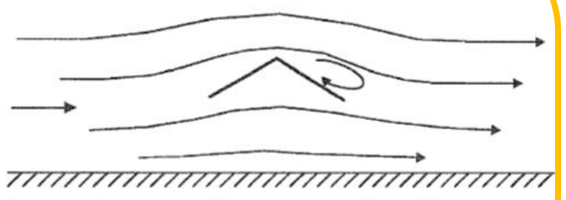


Wind Loads: *Main Codes approach*

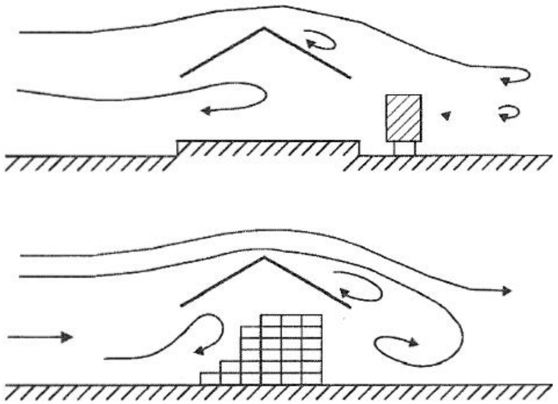
Issues connected with codes are:

- ✓ the **absence of a specific standard** for tracker design, only building codes could be considered;
- ✓ trackers are manly ***design as a generic single canopy roof***,
- ✓ no information about internal and external structure is generally taken into account.

- ➢ A code procedure does not adequately describe the wind interaction among tracker and air flow and represents a **conservative approach**;
- ➢ **CFD** and **Wind Tunnel** tests are the only way to “fill this gap of knowledge”.

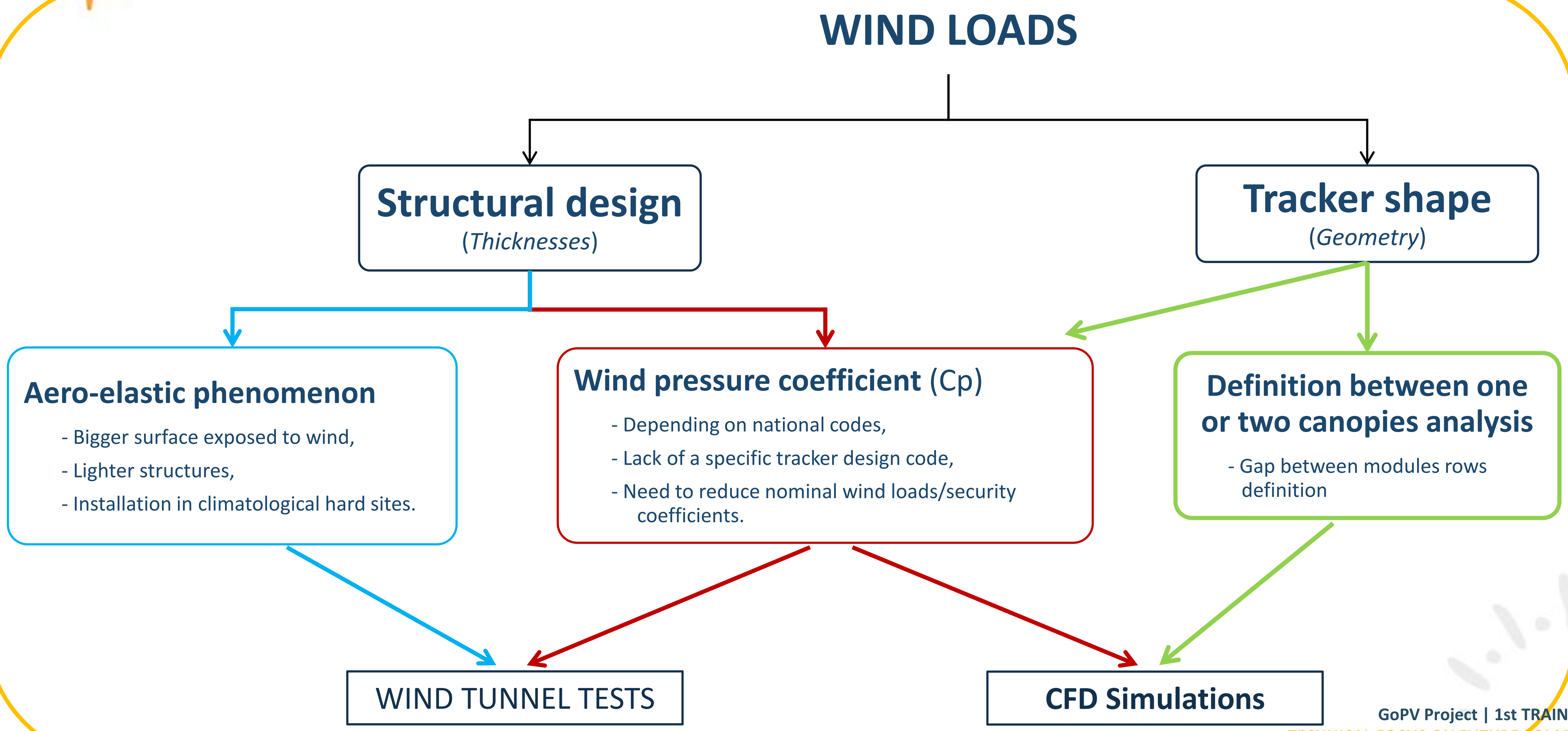


Empty, free-standing canopy (φ = 0)



Canopy blocked to the downwind eaves by stored goods (φ = 1)

Wind loads evaluation: *needs & available approaches*



Wind loads evaluation: GOPV Project

GOPV Specific Issues:

- Wind loads – "Gap effects"
- Wind loads – reliable data for wind coefficients
- Aeroelastic instability data for GOPV -2P Tracker

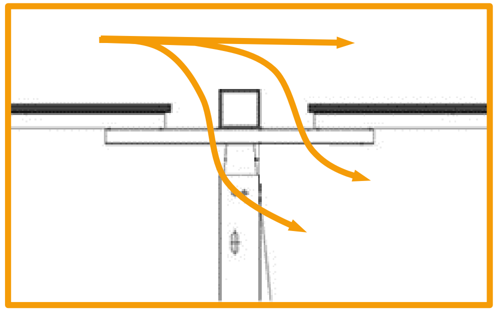
GOPV Approach:

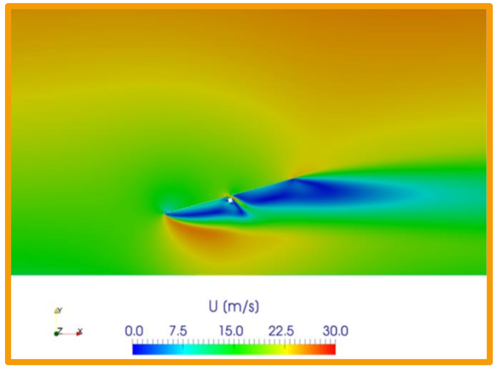
- Wind Tunnel Test, using the "Politecnico di Milano" Wind Laboratory - **GVPM**,
- CFD – Simulations, using **ANSY-CFX** Software
- Collaboration with University of Rome "*La Sapienza*" and *Enginesoft*

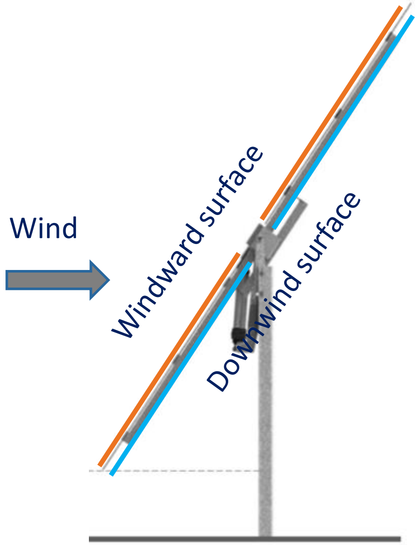
Wind loads – *“Gap effects”*

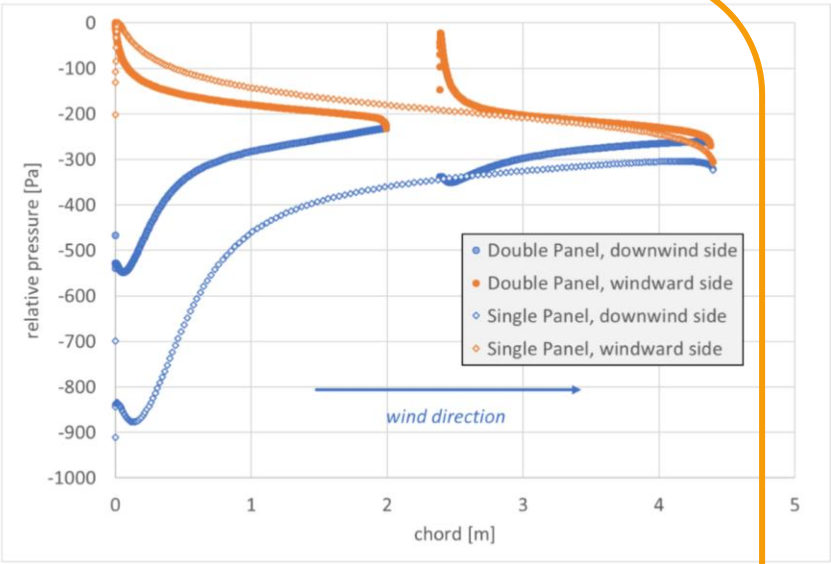
The University of Rome “*La Sapienza*” and *Enginesoft* were involved to support Convert in the develop CDF studies concerning wind-tracker interaction, especially focused on:

- ✓ the role of the gap on a two-portrait-modules tracker has on wind loads actions,
- ✓ how to the wind loads acting on surfaces may **change due to for to different angles of attack**.







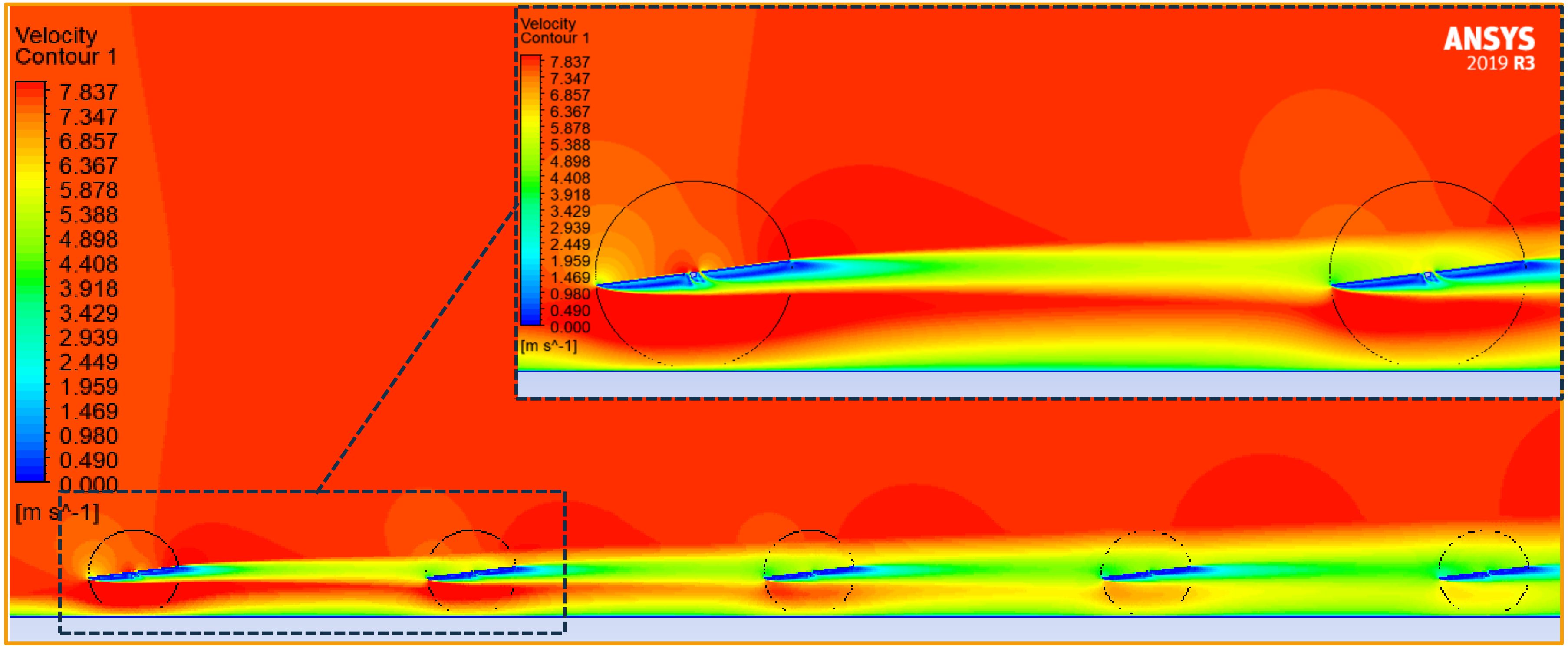


For example in a 5° tilt position the gap produce around 50% of load reduction on the tracker

Wind loads
CFD Simulations - Influence of a multiple tracker array

Study of a multiple tracker array configuration by the CFD analysis:

Shielding effect of the windward rows on the following ones

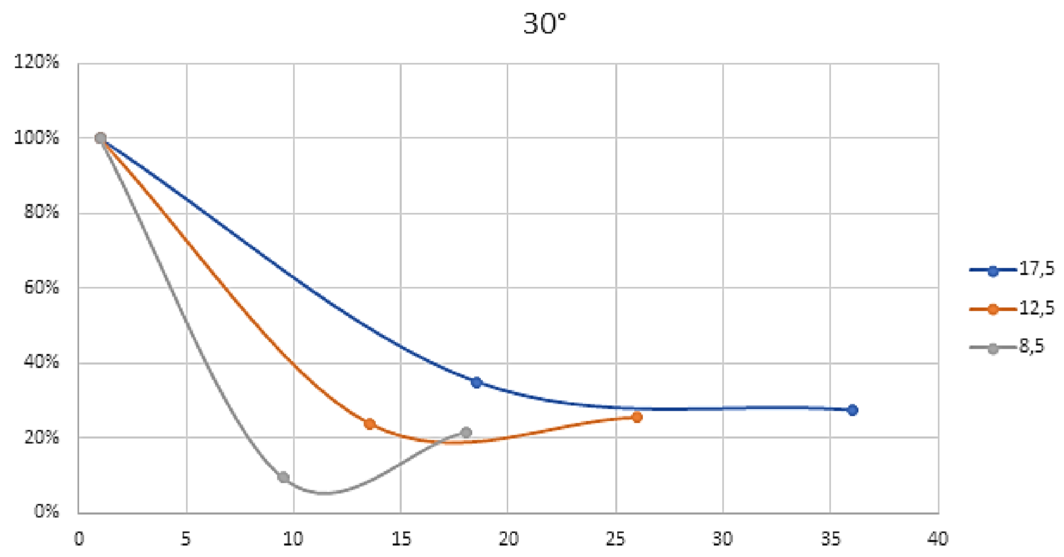


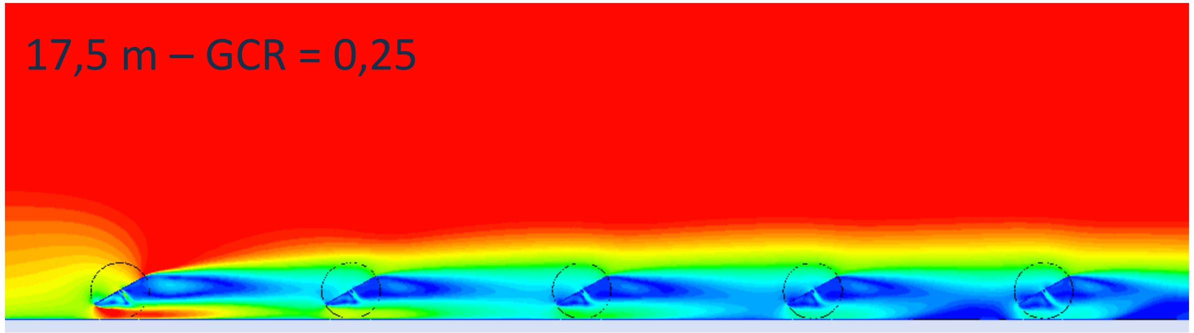
The wind pressure reduction is around 35% starting from the third row

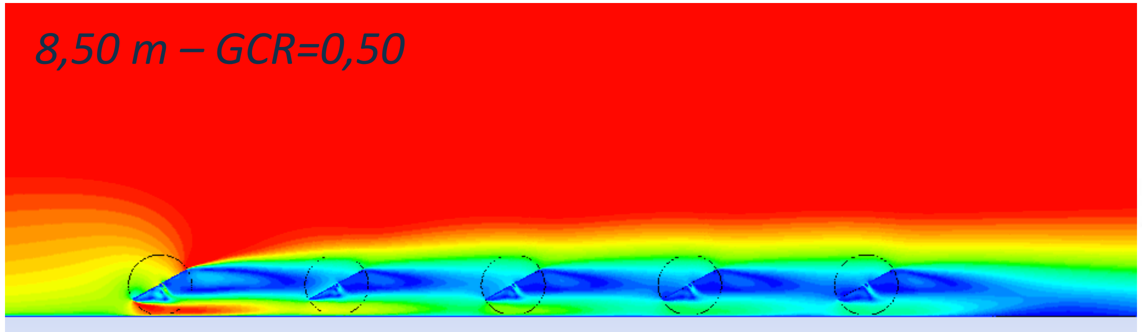
Wind loads

CFD Simulations - Influence of a multiple tracker array

- The influence of a tracker arrays on internal structures it is affected by the GCR (Ground Cover Ratio)
- <u>Lower</u> is the row spacing <u>higher</u> is the sheltering effect: *positive effect on the pressure on modules*



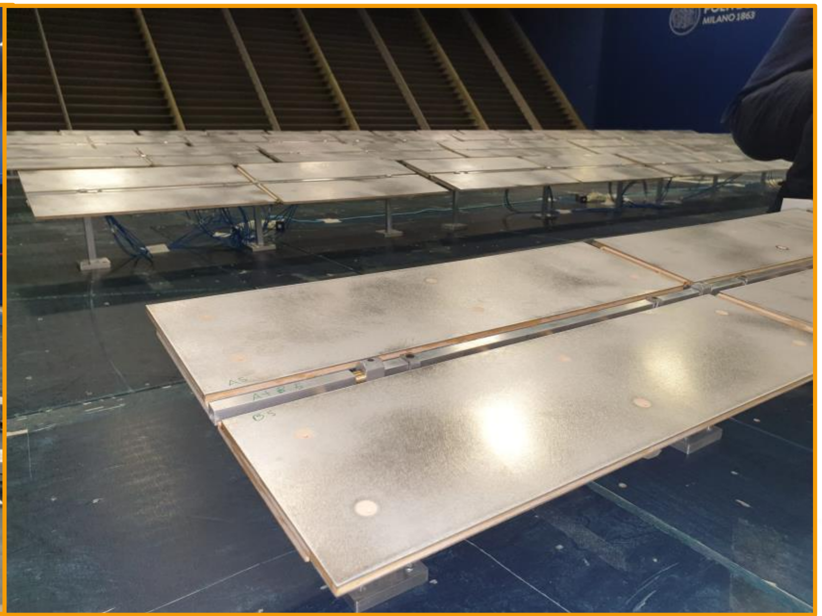




Wind Tunnel Test – Wind Static Loads

Main Reason of Wind tunnel tests:

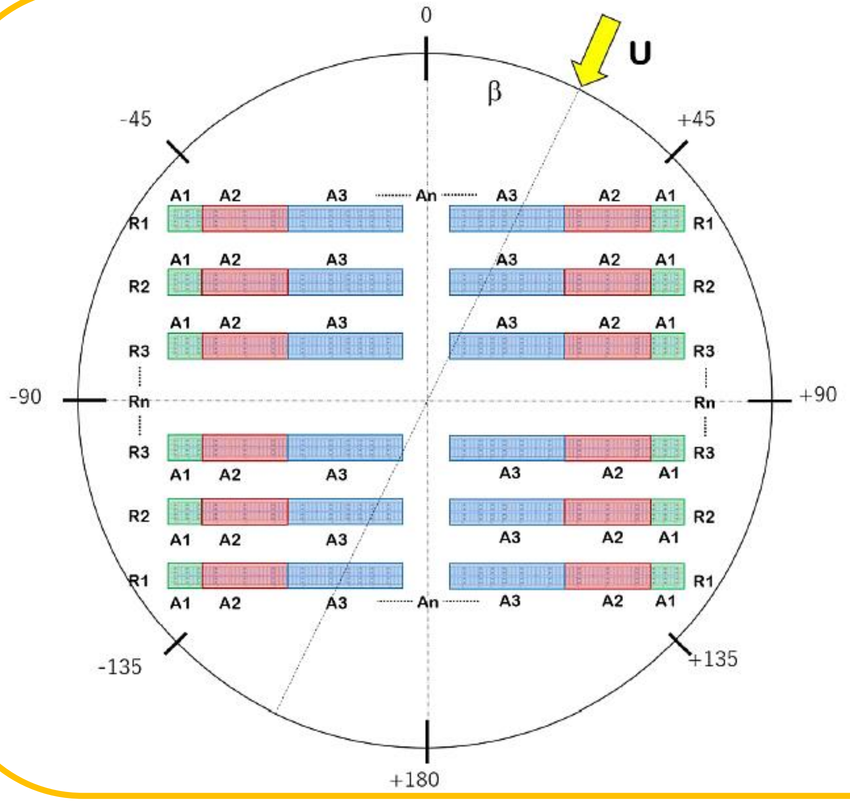
- To provide an experimental support to the CFD analysis: *on both gap and shielding effects*,
- Obtain reliable data for wind coefficients in different plant positions,
- Correctly and safely derogate codes,



→ **Aimed to a more appropriate and cost-effective design**

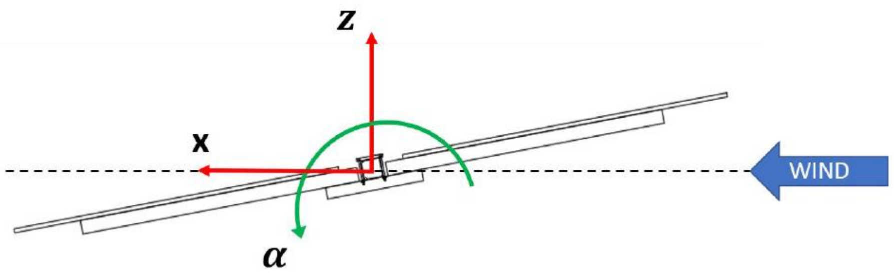
Wind Tunnel Test – Wind Static Loads

Wind tunnel laboratory can provide wind pressure coefficients, distinguish among different tracker position, for different tilt angles and for different wind directions.



Measured parameters

- ✓ Pressure and moment coefficient vs orientation of modules α,
- ✓ Sensitivity of wind loads if changing the distance among modules,
- ✓ Sensitivity of wind loads reduction due to shielding effects of windward structures



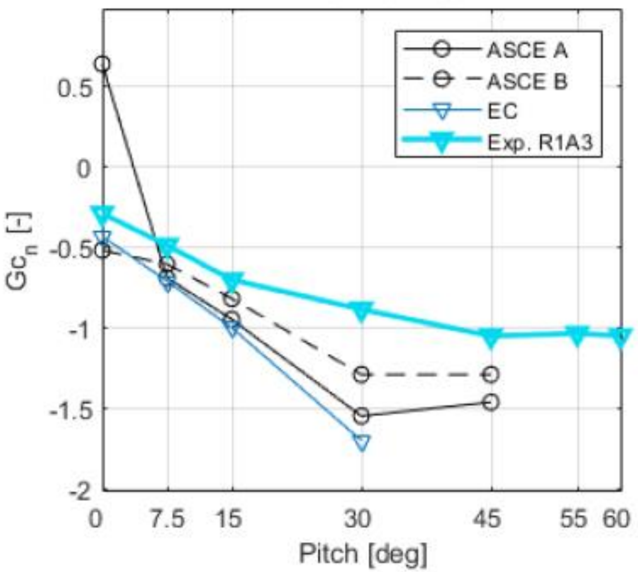
Wind Tunnel Test – Wind Static Loads

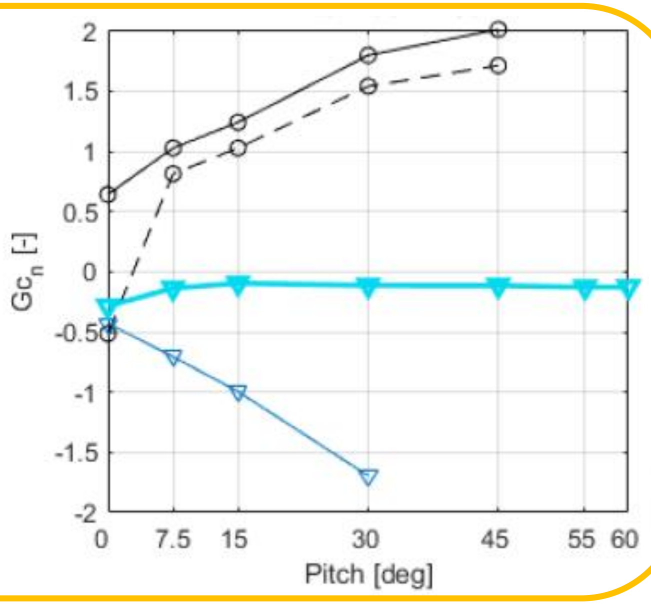
Results

- The WT result is allowing a more accurate plant design, distinguishing among internal and external rows.
- Internal rows are around 80 - 85% of the overall structures: the optimization of their design assure a cost reduction.

Roughly, inner rows suffer:

- ≈ **-40%** pressure and torque reduction in stowing/safety position,
- ≈ **-50%** pressure and torque reduction in service positions.

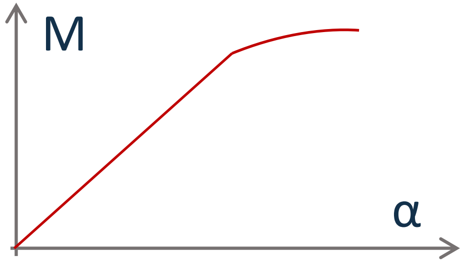


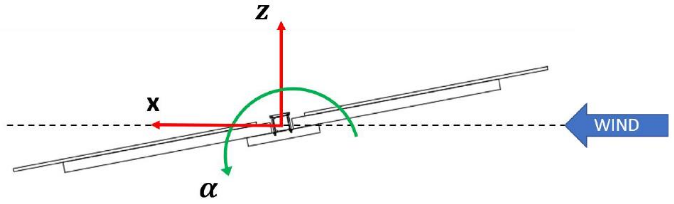


Wind Tunnel Test - *Aeroelastic instability*

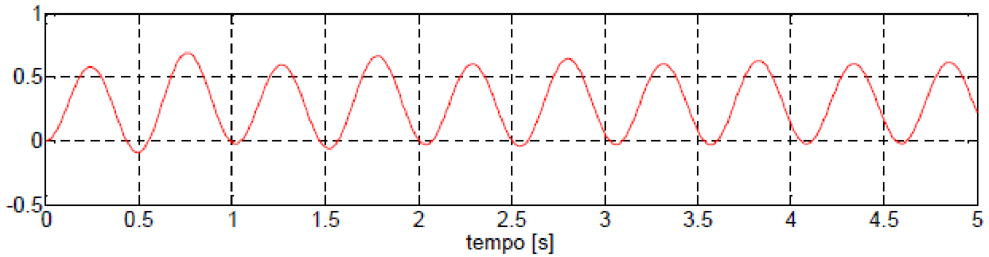
- Nowadays tracker design is heavily focused on aerodynamic instability, especially for the windward rows.
- This turns to be the main and more restrictive design issue.

Torsional static instability *(Divergence)*

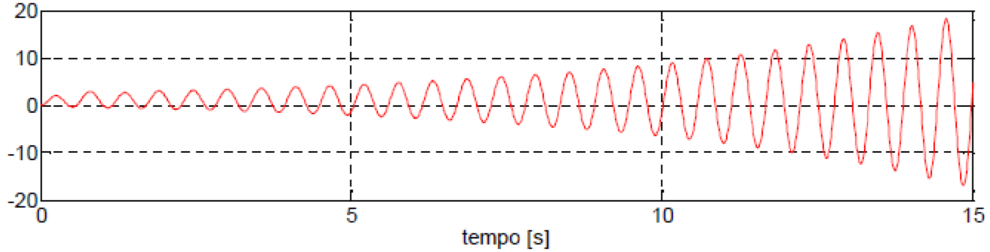




Galloping



Flutter



Wind Tunnel Test - *Aeroelastic instability*

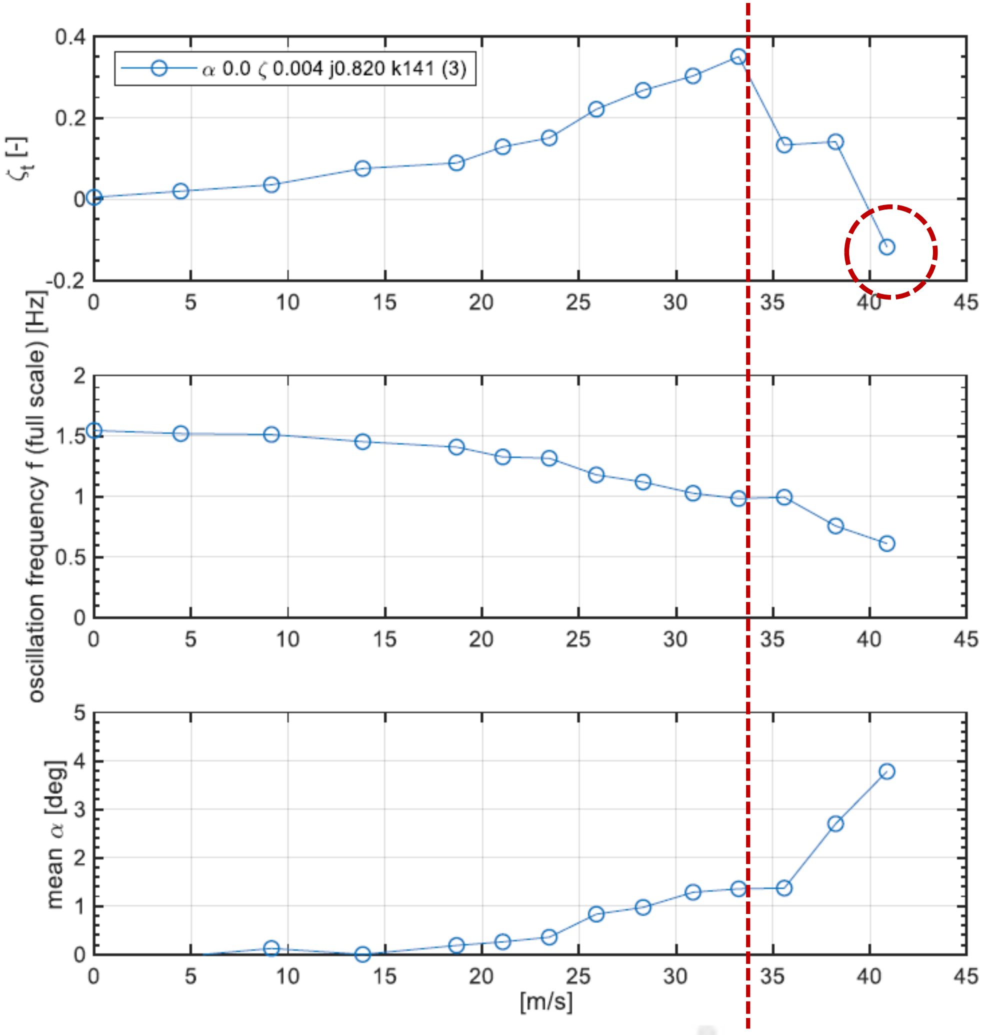
Analyzed ***Aeroelastic instability*** phenomena on GOPV tracker:

- ✓ *Torsional stability – Divergence,*
- ✓ *Flutter,*
- ✓ *Galloping,*

Wind Tunnel Test - *Aeroelastic instability*

Results:

- As long as the tracker-flow ensemble can have an overall damping higher than the forcing in play, the system is in equilibrium.
- As the wind speed increases, the total damping increases up to a peak value, beyond which there is a sharp variation. The full system in no more able to damp forces as before: Vibrations starts.
- Up to the total damping remains as positive value, vibration amplitude remain “constant” without being destructive,
- Once the total damping become a negative value, the tracker-flow interaction increase up to a destructive event.



Aerodynamic Design of GOPV 2- P tracker

Aeroelastic instability phenomena:

- ***Torsional stability – Divergence:***

  *only in **Stow** position (0° +/-1°) – stable up to **35 m/s (*)***

- **Dynamic Instability Flutter:**

  *All other **Service** positions – stable up to 23 m/s (*)*

  ***Not Galloping** in the same range of wind velocity*

***(*) Note**: velocity are referred to 10minutes averaged values measured at 10m height above ground.*

To scale at gust factor a multiplier x 1,46 is suggested

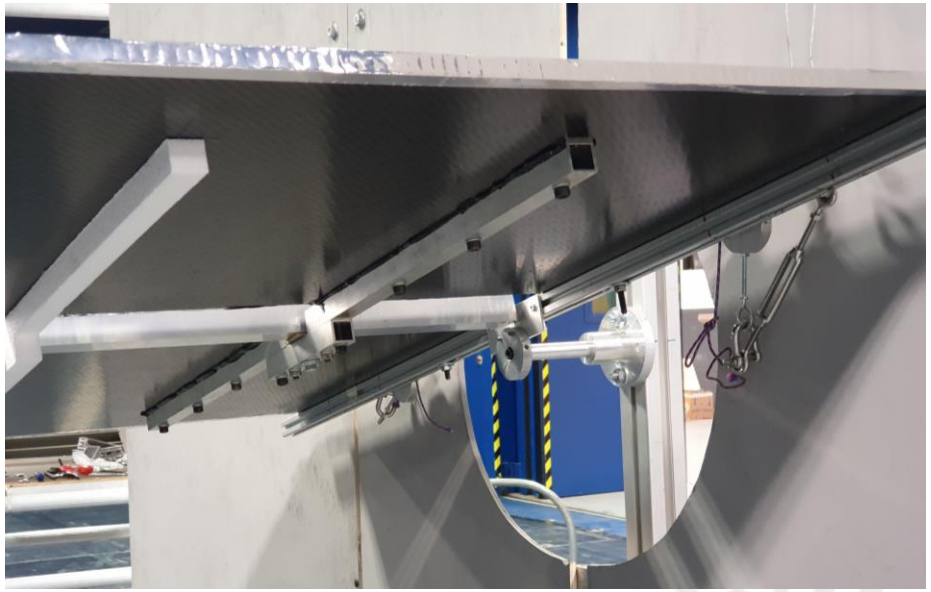
Wind Tunnel Test - Aerodynamic

Design – Spread Results

To understand the results obtained in the tunnel are obviously related to a model, which has certain mechanical properties of stiffness, mass and damping. It is therefore necessary to scale those results to the single project case by case.

The comparison between *model* and *project* could be developed thought:

- Reduce velocity parameter, $\left[\frac{V}{\mathrm{f \cdot B}}\right]_m = \left[\frac{V}{\mathrm{f \cdot B}}\right]_p$
- Mass ratio, $\left[\frac{m}{\rho B^2}\right]_m = \left[\frac{m}{\rho B^2}\right]_p$
- Damping scale. $Sc_m = Sc_p$



PV TRACKER – DESIGN & CONTROL *Convert Italia*

General Topics	***Speaker***	***Time***
Introduction to Tracker Device for PV plant. Mono axial tracker Concept Design: performances vs reliability	*G. Demofonti*	*10 min*
Structural Design of mono axial tracker	*A. Ricci*	*20 min*
Structural Design of mono axial tracker: Wind Loads and Aerodynamic design	*A. Ricci*	*20 min*
Questions & Answers	**All**	***10 min***
Criteria for the evaluation of corrosion resistant of tracker operating in aggressive environment	*G. Demofonti*	*20 min*
Electronic control board and powering system of mono axial tracker	*A. Timidei*	*15 min*
Failure modes, Qualification of tracker and Maintenance actions	*G. Demofonti*	*15 min*
Questions & Answers	All	*10 min*

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

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Thank you for your attention.

Please Questions !

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