Strategies to Mitigate Wind Related Risks in Trackers Compatible with Ultra-High Power Modules

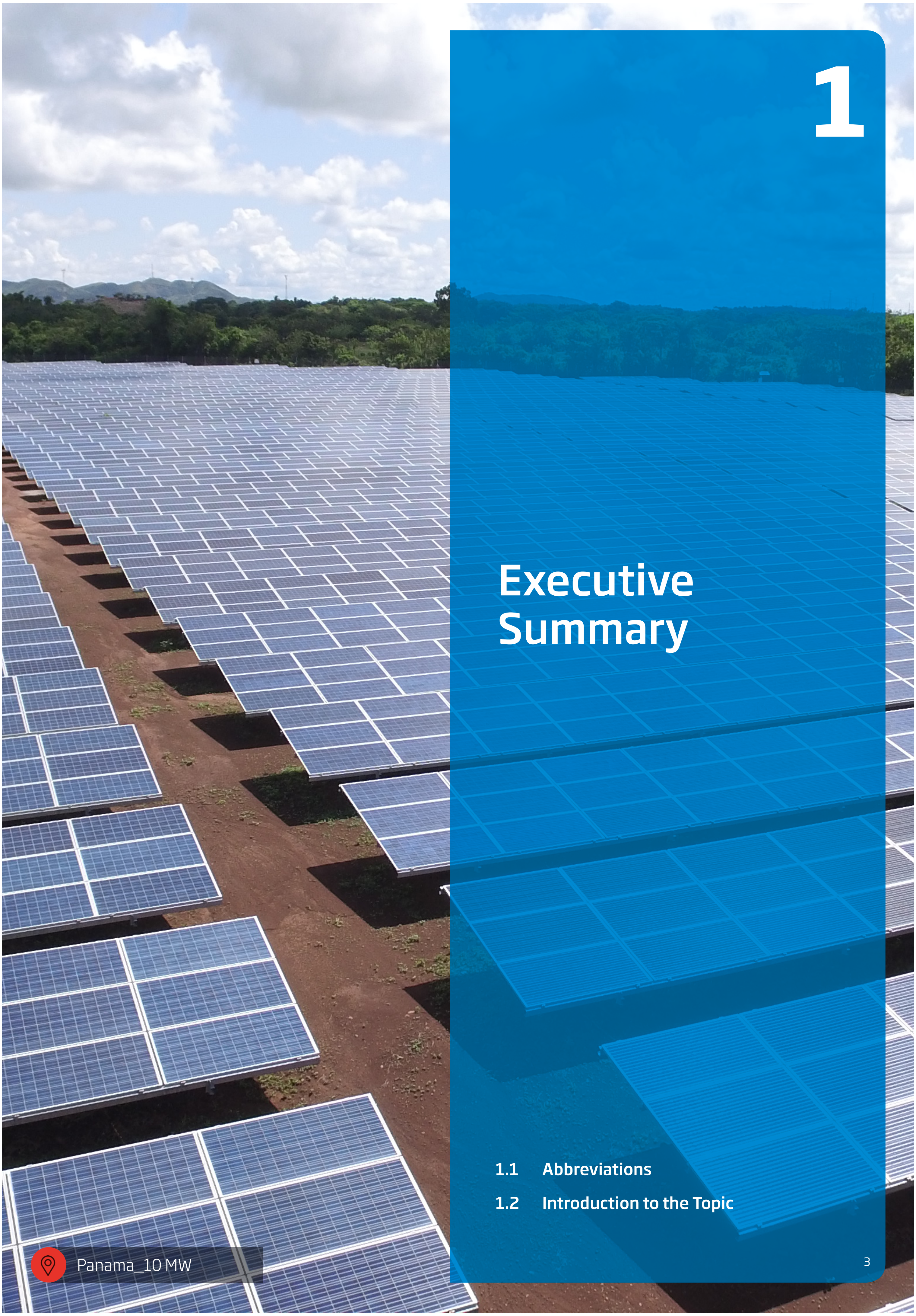
July 2021

White Paper

TrinaTracker

Content

TrinaTracker



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Executive Summary

1.1 Abbreviations

BOS	Balance of System (cost of all components of a PV system other than the modules)
W	Watt
RWDI	Rowan Williams Davies & Irwin Inc. (wind consulting engineering firm)
CPP	Cermak Peterka Petersen Inc. (wind engineering consultants)
DOE	Design of Experiments
IEC	International Electrotechnical Commission
UL	Underwriters Laboratories
P	Portrait
PV	Photovoltaic
DAF	Dynamic Amplification Factor
GCN	(external) Gust (pressure) Coefficient Net
O&M	Operation and Maintenance
FEM	Finite Element Method
NCU	Network Control Unit
R&D	Research and Development
AMFE	Feature and Design Model Analysis
SCRA	Sign, Cause, Remedy, Action
NPR	Risk Priority Number
LCOE	Levelized Cost of Energy
WTT	Wind Tunnel Test

1.2 Introduction to the Topic

The photovoltaic industry has experienced a tremendous evolution over the past two years, leading to higher energy production and lower installation costs.

The solar business has entered into a new-module-era characterised by the production of the 600W + ultra-high power modules, which leads to a considerable increase in yield generation and a BOS reduction.

The mounting of large modules requires new geometrical and electrical features to incorporate bigger wafers and a configuration of lower open-circuit voltage, higher short circuit current, and a new string design.

The most critical challenge of the photovoltaic installation in this new era is the reconfiguration of tracker design. The accommodation of 600W + involves a higher pressure of wind load on the system that affects the trackers' stability and reliability.

Therefore, the most critical challenge of the photovoltaic installation in this new era is the reconfiguration of tracker design, since the accommodation of 600W + involves a higher pressure of wind load on the system that affects the trackers' **stability** and **reliability.**

TrinaTracker has focused its research and engineering resources on accomplishing an optimum adaptation of the tracker design parameters to solve any issue originating from the large dimensions of the panels, like the impact of **higher wind pressure** on the modules. **TrinaTracker**, in collaboration with leading wind engineering experts, **RWDI** and **CPP**, has accurately adapted the trackers' design to mitigate risks and guarantee optimum energy production and system reliability.

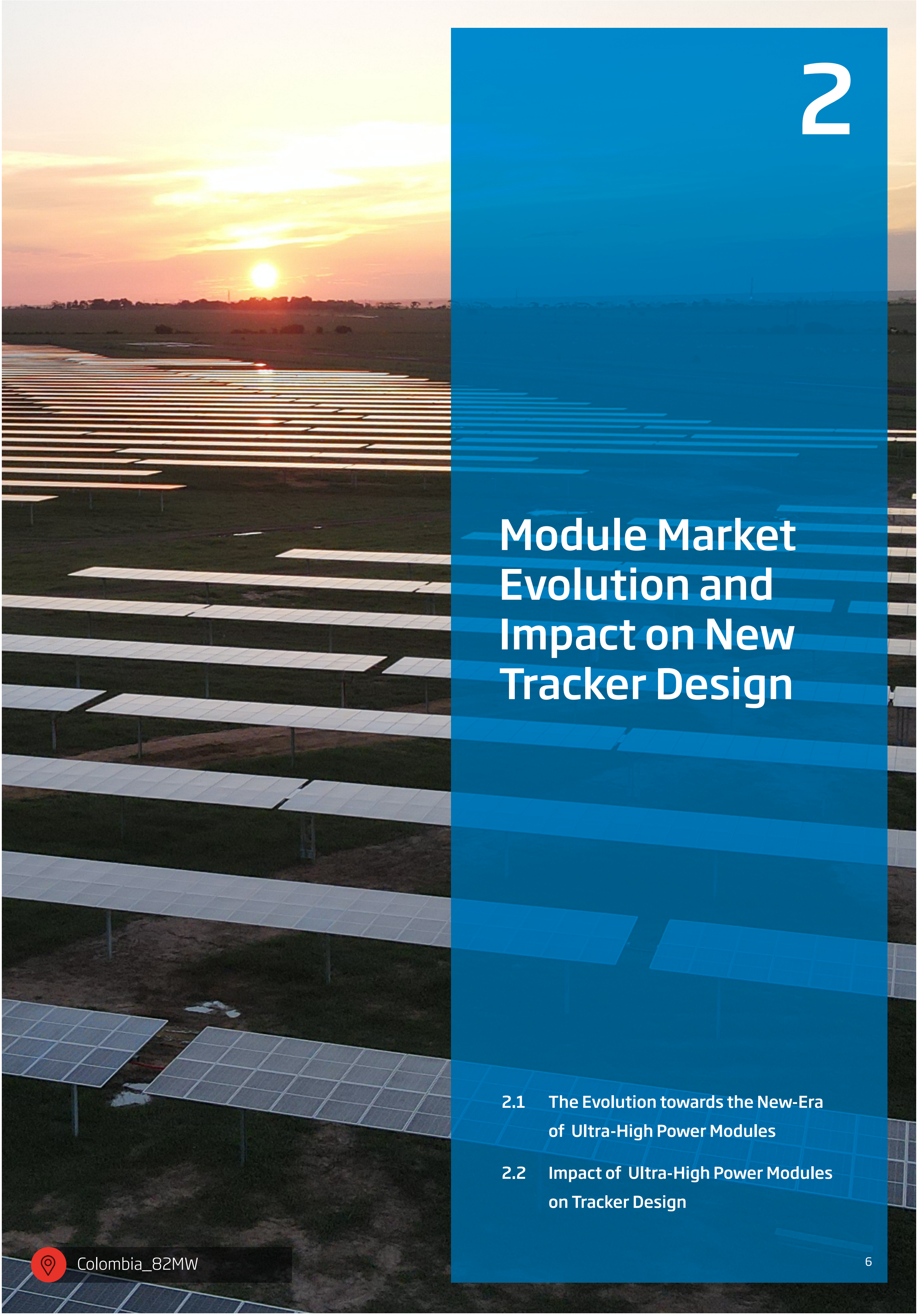
Dynamic and **aeroelastic** effects and analysis of external wind load represents crucial factors in tracker design compatible with large-format modules.

Comprehensive DOE and module pressure testing activities are conducted to provide **State-of-the-Art** design engineering solutions and validate the effect of wind loads on modules and trackers while complying with IEC and UL standards.

With this, **TrinaTracker**'s **Vanguard 2P** and **Agile 1P** series, compatible with 600W + modules, have been upgraded according to the results gathered from the multiple tests and calculations performed on the systems to guarantee optimum energy production, excellent performance and minimum O&M services.

1P and 2P trackers adopt an individual design approach due to architectural differences, with aeroelastic instability and wind pressure analysis on modules being critical factors in the system´s design.

The data gathered from wind analysis and tests notoriously improve the calculation methodology that defines the requirements to upgrade the tracker design. The key elements of the new design are the introduction to a new **multi-drive system** for 2P structure to increase the torsional stiffness and the definition of the **new stow position** established for 1P trackers.



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Module Market Evolution and Impact on New Tracker Design

2.1

The Evolution towards the New-Era of Ultra-High Power Modules

The module industry experienced some substantial changes from the beginning of the millennium until 2014. However, the arrival of **bifacial** modules in 2018 represented a significant technological milestone, which was followed in 2019 by the production of large-format modules to accommodate broad wafers (M10:182x182mm and M12: 210x210mm).

The widespread availability of large-format modules and the increase of energy generation brought about a significant **reduction in system cost**. Furthermore, the need arose of accommodating technology changes in the PV systems, since ultra-high power modules add significant weight and require mechanical and electrical **adaptations** in trackers, to guarantee optimum yield and efficiency.

TrinaSolar, a leading module manufacturer and system solution provider with consolidated experience in module R&D, engineering and tracker design, prioritises aeroelastic stability and module compatibility in the process to create a tracker design that guarantees energy production and system reliability when accommodating large-format modules.

Large-format modules add significant weight and require mechanical and electrical adaptations in trackers

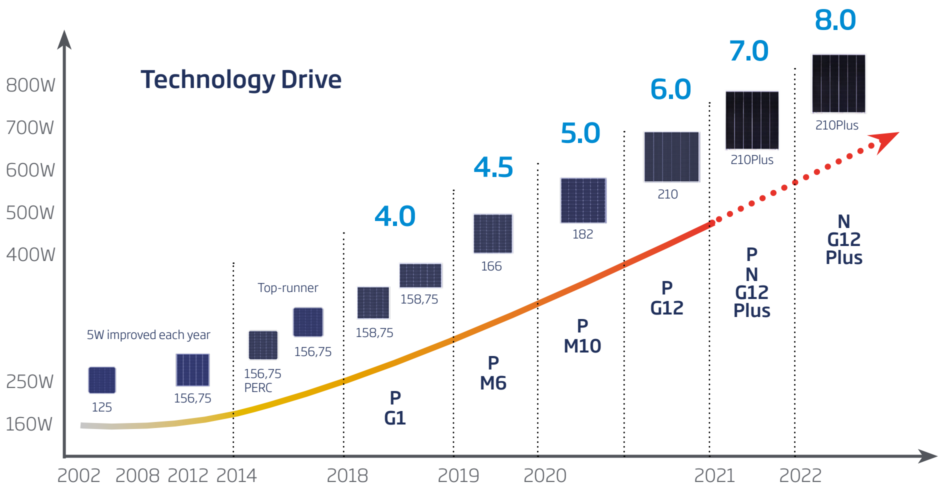

Image 1 - Chart: PV cell technology roadmap from 2002 to 2022

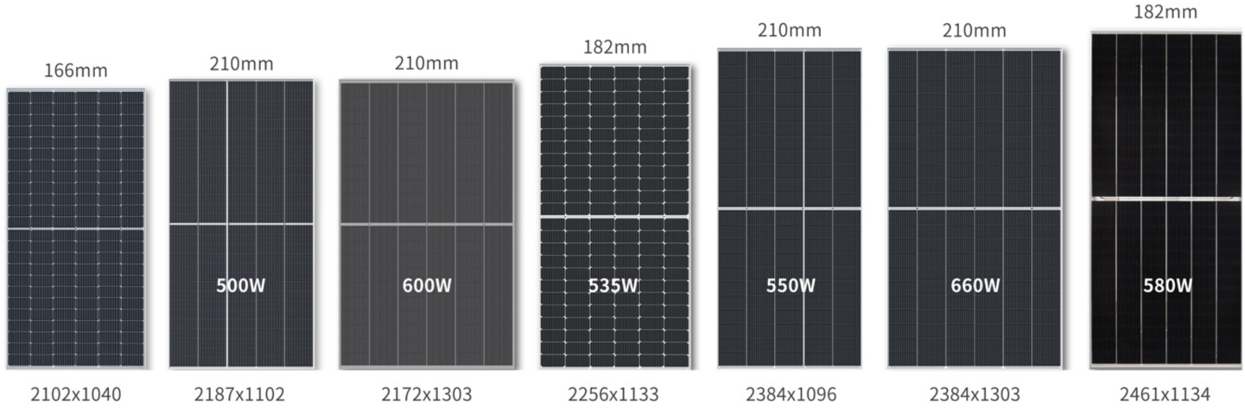

Image 2: PV module size change

Change Of Module Parametres 2018 - 2021

Timeline		2018	2019H1	2019H2	2020H1	2020H2		2021H1	2021H2
Power (Watt)		370	400	450	500	550		600	660
Wafer Type		157mm	158mm	182mm	210mm	182mm	210mm	210mm	210mm
Frame Thickness (mm)		35	30	35	35	35	35	35	35
Electrical	VOC (V)	48.3	49.9	49.3	51.5	49.5	38.1	41.7	45.9
	ISC (A)	9.83	10.39	11.6	12.13	13.85	18.39	18.42	18.45
	Toc* (%/°C)	-0.29	-0.25	-0.27	-0.25	-0.28	-0.25	-0.25	-0.25
Mechanical	Size (mm)	1960x992x35	2024x1002x30	2094x1038x35	2187x1102x35	2256x1133x35	2384x1096x35	2172x1303x35	2384x1303x35
	Size increase %	base	4.3	11.8	23.9	31.5	34.4	45.6	59.8
	Weight (Kg)	21.5	26	23.3	30.1	32.3	32.6	35.3	38.7

Image 3 - Table: Module technology roadmap

2.2 Impact of Ultra-High Power Modules on Tracker Design

The design and configuration of solar trackers are closely related to the dimensions of the photovoltaic panel.

The installation of large-format modules implies subject to different dynamic behaviour in tracker structure, including heavier loads.

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The use of large-format modules requires longer chords, longer rows, stronger structures and, overall, more robust cross-sections to structurally bear the **extra weight** and conserve stability against **wind effects**.

The electrical configuration of the tracker is also affected by the mounting of ultra-high power modules due to the change in the number of strings (modules connected in series) assembled in a row.

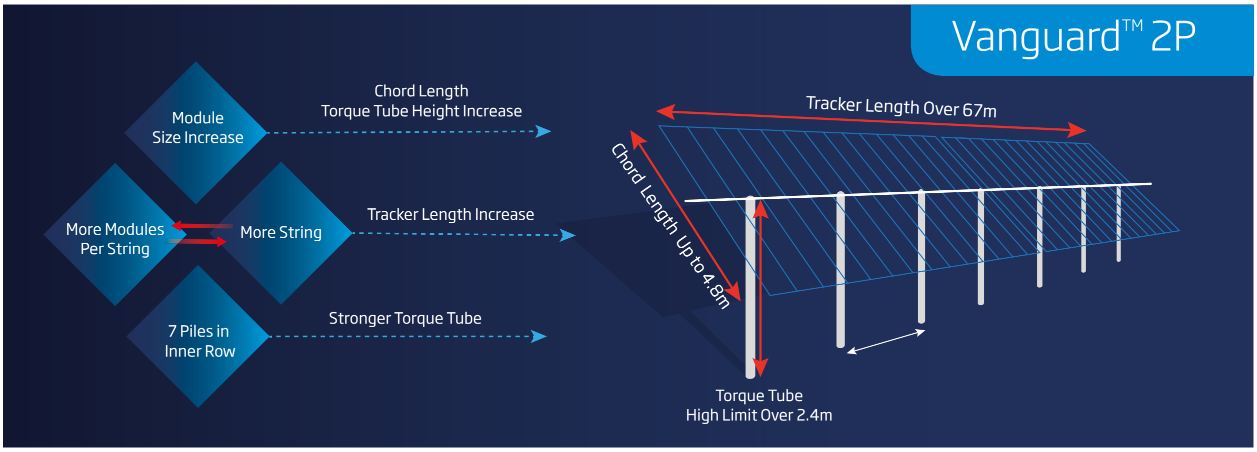


Image 4: Impact of large-format modules on the tracker's structure

The accommodation of large-format modules means that the **central mass** of the module is located further away from the torsional centre of the tracker. Therefore, the torque tube will have lower torsional natural frequencies for the same configuration.

Usually, more weight moved further away from the torsional centre of the tracker implies **lower natural frequencies** and **damping changes**; hence, the use of longer chords requires more refined aeroelastic calculation.

Ultra-high power modules require longer trackers to be accommodated for the same number of panels

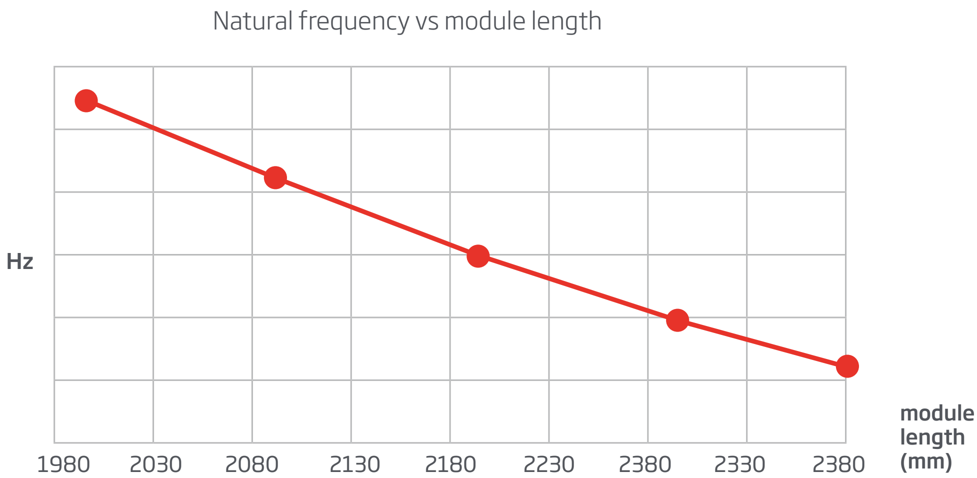


Image 5 - Chart: Natural frequency vs module length

Ultra-high power modules require **longer trackers** to be accommodated for the same number of panels. The installation of longer trackers involves higher risks of instability and the challenge of dealing with **higher torsional deflections**.

The solution to this issue includes the installation of **stiffer torque tubes** or **torsional locks** along the length of the tracker or combining both structural elements. Additionally, a longer tracker means lower frequencies if the traditional central drive is kept.

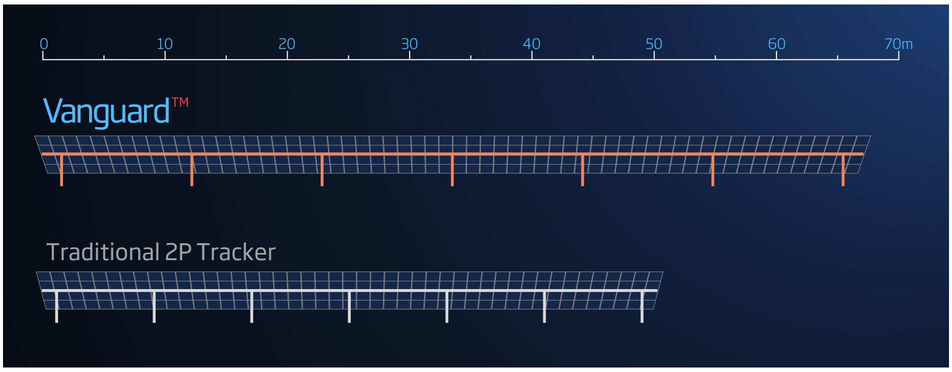


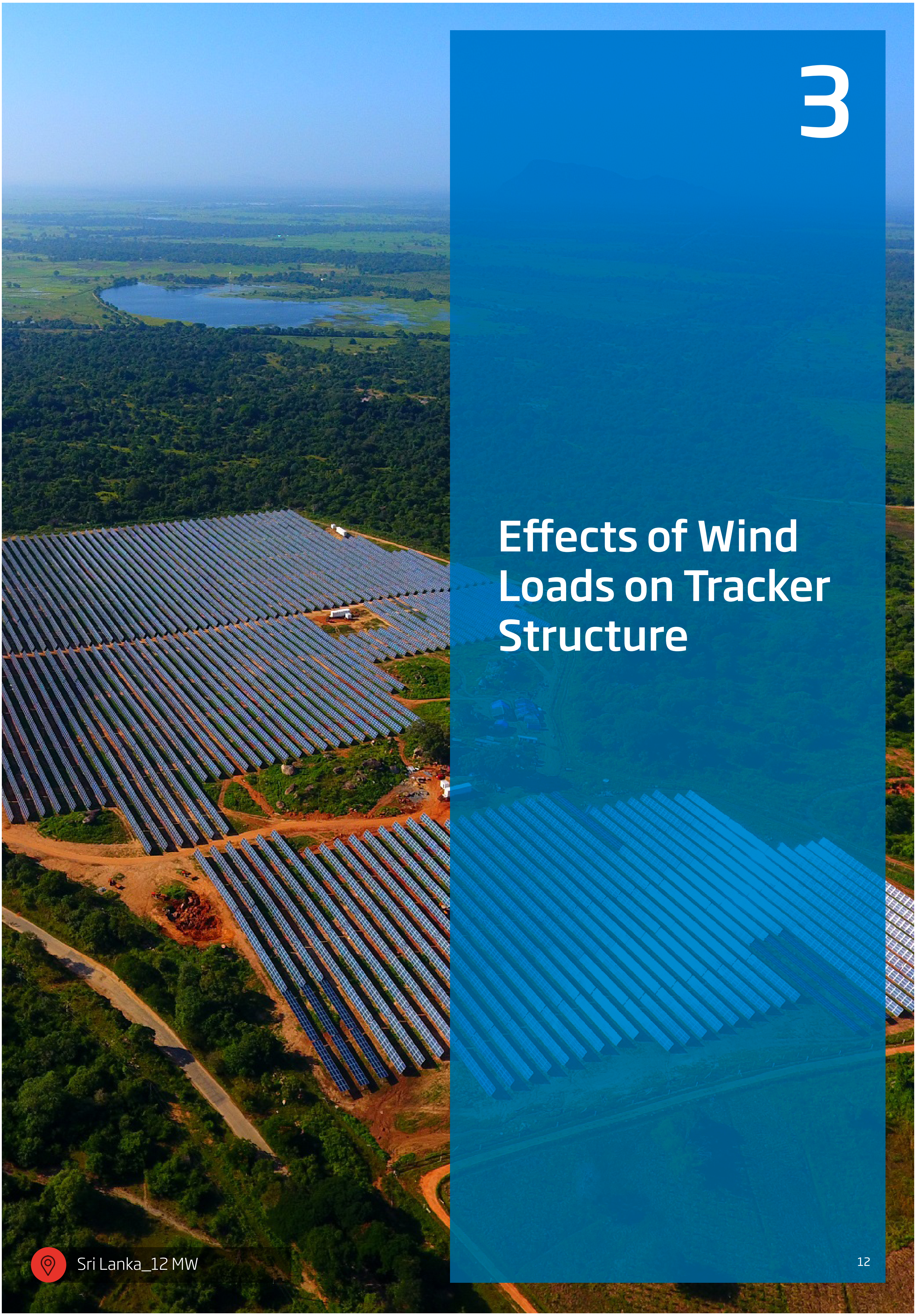
Image 6: Impact of ultra-high power modules on the tracker's length

Higher load pressure on modules involves **higher foundation reactions** for the same number of piles. Foundation reactions are one of the reasons why **TrinaTracker** defines a stow position at low tilt angles for the 2P configuration trackers.

The following table summarises the crucial modifications performed in solar trackers to run with ultra-high power modules and maintain system reliability.

Module Changes	Changes in Tracker Stiffness and Stability	Impact on Tracker/Components Design
Length increase	Chord increase High effect on aeroelastic critical wind speed	Higher structures Adjusted stow strategy
Width increase	Longer rows Lower torsional stiffness	Improved drive system
Surface increase	Higher wind load on module surface Higher torque on lock systems Higher foundation reactions	Bigger tracker surface Stiffer purlin Strengthened tube Higher post
Mass increase	Lower natural frequency Changes in damping High effect on aeroelastic critical wind speed	Improved drive system Adjusted stow strategy

Image 7 - Table: Most important changes in solar trackers for accommodating ultra-high power modules



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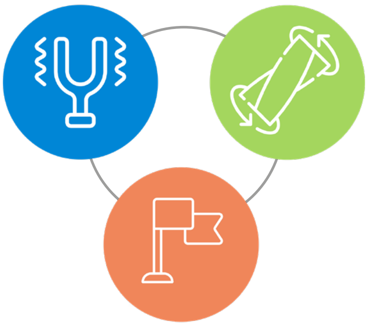
Effects of Wind Loads on Tracker Structure

3 Effects of Wind Loads on Tracker Structure



The structural wind load distributions were determined by considering the mean (steady) and fluctuating wind loading for **aerodynamically** important **wind directions**. The fluctuating portion of the wind loads is due to wind turbulence (buffeting) and the dynamic response of the structure (resonant vibration). For flexible, lightly damped structures, the inertial loads due to resonant vibration can add a significant contribution to the fluctuating wind loads. To date TrinaTracker with **RWDI** research has become aware of three mechanisms for wind to cause vibration or instability in sections of a solar installation.

Resonant Vibration

Wake effect resonance caused by turbulence generated from the first row of an array causing resonant vibration in subsequent rows.

With regard to **resonant vibration**, increased dynamic buffeting response of downwind trackers occurs due to the increased energy over narrow-banded frequencies related to shedding of vortices from upwind rows. This type of increased excitation is captured by the dynamic amplification factors in the static pressure data. The likelihood of this occurring is therefore dependent on the natural vibration frequency of the structural system, wind speed, chord length, as well as the damping in the system.

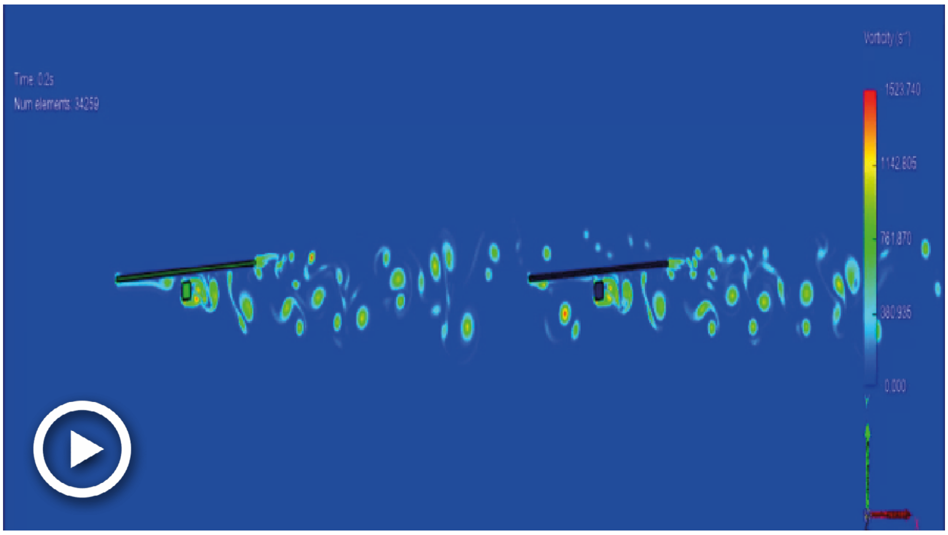


Image 8 - Video: Buffeting

Flutter

For systems relying on a central torque tube driven from a single location, a torsional vibration mode is possible, created by a form of flutter generally initiated at the ends of the row.

Flutter is a **self-excited aerodynamic oscillatory instability** in which the aerodynamic forces depend on the motion of the structure itself and can lead to very large amplitudes in torsional motion or coupled torsional and vertical motions.

Flutter occurs when the energy imparted by the aeroelastic forces cannot be dissipated by the system damping.

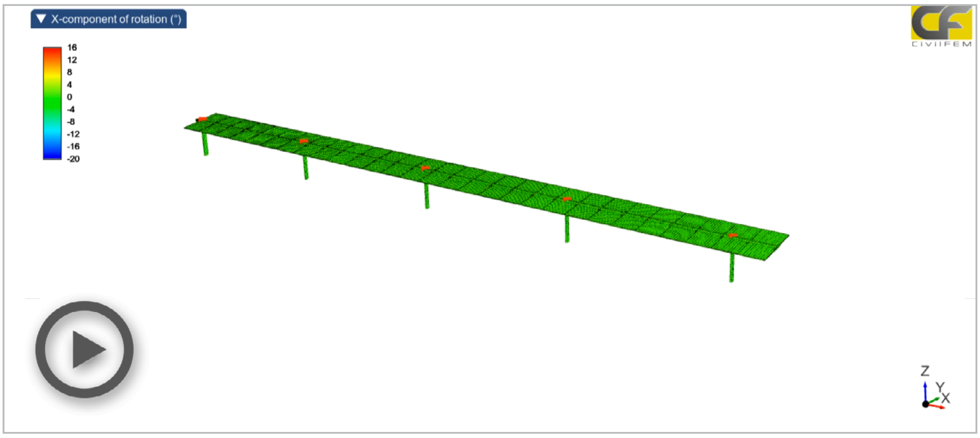


Image 9 - Video: Flutter

Torsional Divergence/Galloping

For systems relying on a highly flexible central torque tube, the change in torque applied to the row as it rotates can overpower the torque tube's ability to resist, resulting in an effect known as torsional divergence.

In comparison, torsional divergence is a non-oscillatory instability where under a given wind speed the structure deflects torsionally due to the **aerodynamic pitching moment**. This deflection effectively increases the angle of attack which can increase the aerodynamic pitching moment acting on the structure, further increasing the deflection.

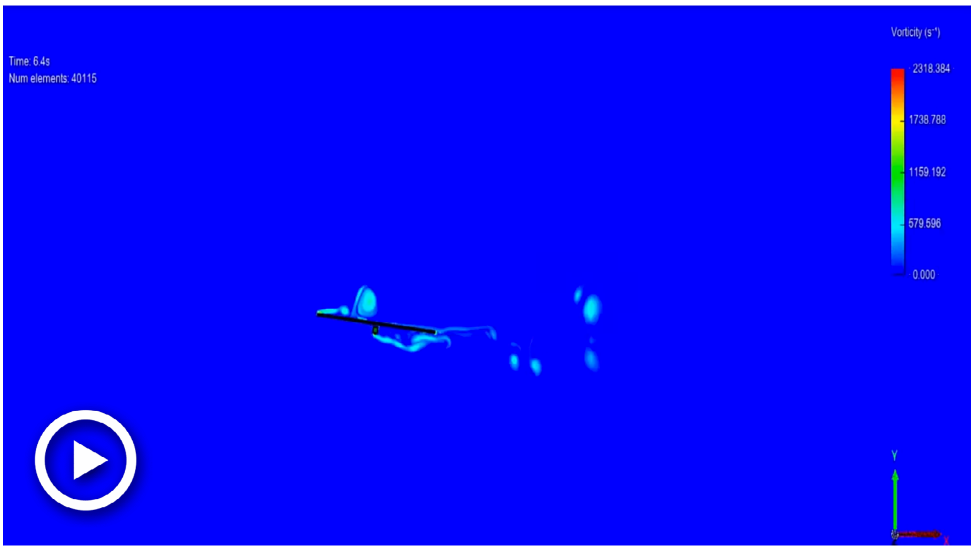
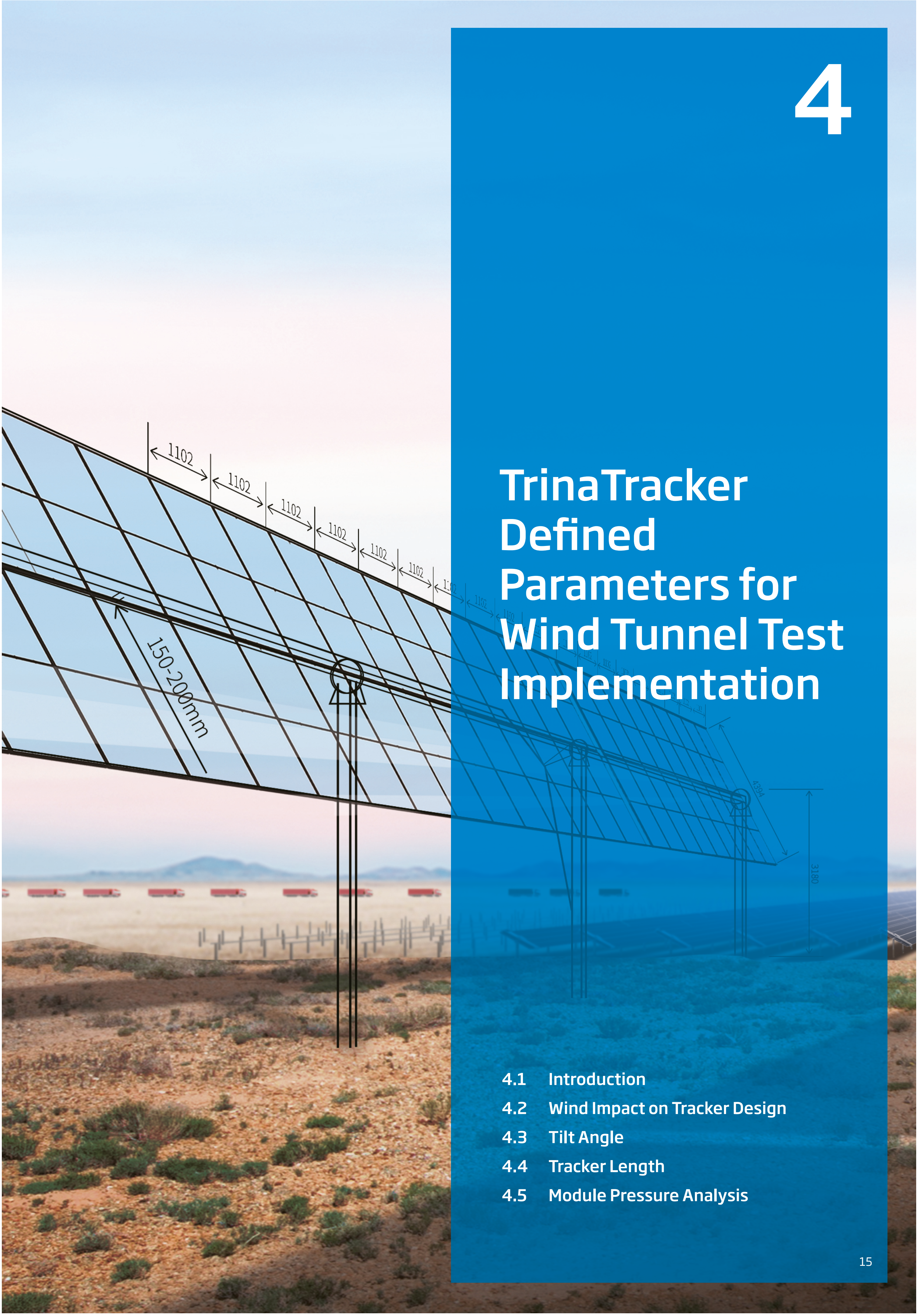


Image 10 - Video: Torsional divergence



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TrinaTracker Defined Parameters for Wind Tunnel Test Implementation

4.1 Introduction

TrinaTracker produces **Agile 1P** and **Vanguard 2P** scale prototypes according to specific defined parameters of tilt angle, tracker length and module pressure. These prototypes are subjected to dynamic and static loads through tunnel test implementation.

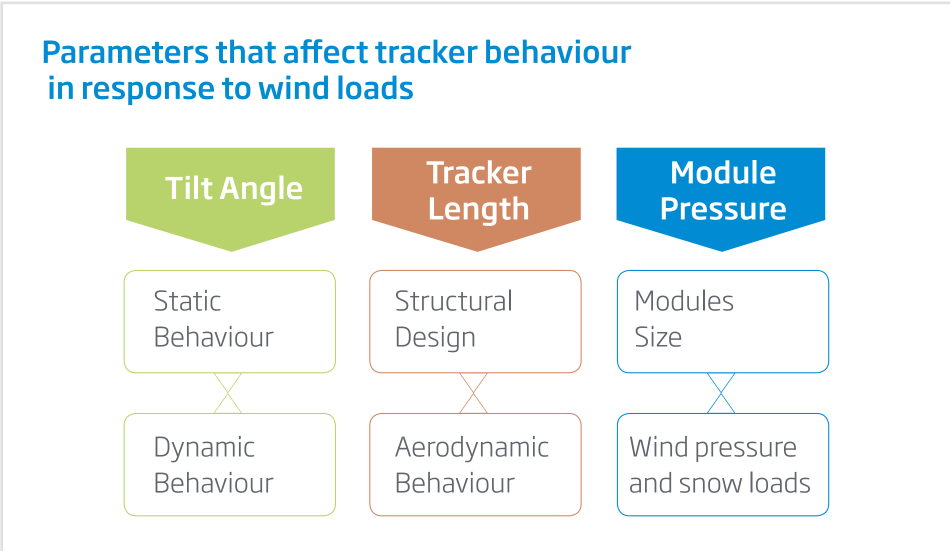


Image 11 (1&2): Loads and structure design

4.2 Wind Impact on Tracker Design

The most critical wind impact on trackers is the torsional motion which occurs when wind speed exceeds the limit allowed by the tracker structure. The resulting effect is an uncontrollable torsional vibration that causes instability in solar trackers.

Tracker structures comprise a **central torque** tube with piles evenly distributed in between.

Tracker structures that accommodate large-format modules are prone to suffering from different **torsional aerodynamic instabilities**, depending on their geometry and dynamic properties (frequency, damping).

The most critical wind impact on trackers is the torsional motion which occurs when **wind exceeds the speed tolerated** by the tracker structure. The resulting effect is an uncontrollable torsional vibration that causes instability in solar trackers.

The static torsional loads resulting from lower wind speed are also considered when designing tracker structure.

Instability is avoided by calculating the critical wind speed, and then, taking the result into consideration when defining the tracker design.

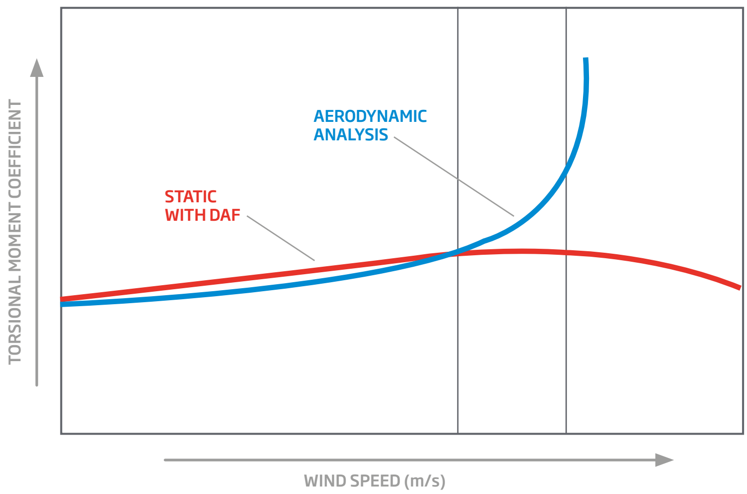


Image 12 - Chart: Static torsional and aerodynamic loads

The two tracker configurations addressed in this paper (1P & 2P) require two **different design approaches**. **TrinaTracker** follows different design criteria depending on the tracker's features, and the resulted insights gathered from the tunnel tests performed in collaboration with the leading engineering wind consultancy firms on the market: **RWDI** and **CPP**.

4.3 Tilt Angle

Advanced analysis show that different design must be adopted to define the tilt angles of the structure.

As result, **high tilt angles** are governed by **static loads**, while **stiffness** defines the design at **low tilt angles**.

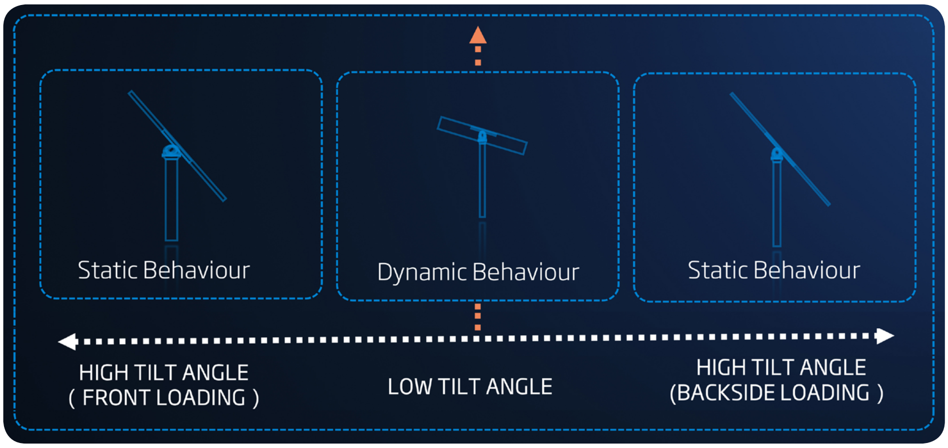
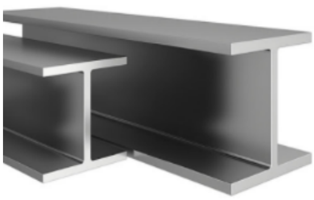


Image 13 - Chart: Tilt angles and structure behaviour

STATIC BEHAVIOUR

Static loads, both pressure coefficients and dynamic amplification factors, govern the design at high tilt angles.

Critical structure pieces and components are designed according to the data resulting from static and **torsional loads analysis**.



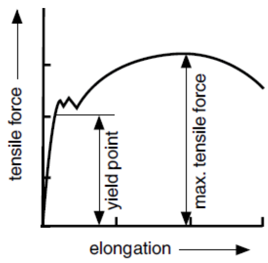


Image 14 (1&2): Loads and structure design

DYNAMIC BEHAVIOUR

Aerodynamic loads define the tracker design at low tilt angles. Stiffness and damping parameters are fundamental inputs for this scope. The stiffness of the structure can be increased by including a multi-actuator system and/or robust design that allows effective wind mitigation at low tilt angles.

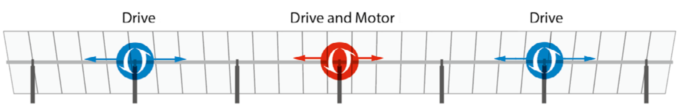
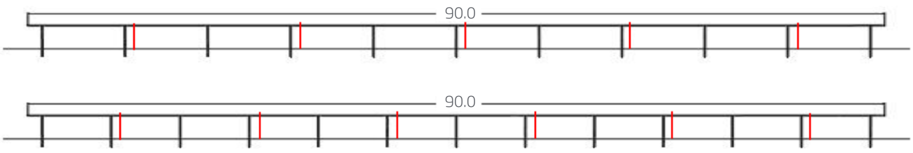


Image 15: Multi-drive system

4.4 Tracker Length

Tracker length is defined by the number of modules assembled in a row, which depends on the number of strings that can be fitted in one tracker.

On the basis of these figures, it is normal to draw up a hypothetical configuration of the structure, like the one in the example shown below. However, a **risk analysis** of the structure must be performed to validate it as the final tracker design. The fact of not considering the risks associated to a particular tracker length can be detrimental to the stability of the project and production yield.



OUTER	Vanguard	4 strings	90m	13 piles	6 linear actuators
INNER	Vanguard	4 strings	90m	11 piles	5 linear actuators

Image 16: Hypothetical components strategy for a 90m tracker length configuration

The following risks were encountered, after analysing the wind impact on an alternative **TrinaTracker** 2P configuration structure, with a length of 90 metres. The potential threats resulting fom the analysis confirm that a longer design is not always the most efficient solution to ensure reliability and optimum energy production.

Dynamic Issues

Longer trackers are inherently more unstable when supporting dynamic loads. They require extra reinforcement which results in increased structure cost. The awareness of this issue led to the need for **TrinaTracker**'s engineering department to optimise the system design from a cost perspective.

Lower Installation Tolerances

Trackers with longer spans laid on sites with steep slopes increase construction costs and entail higher risks. Steep slopes involve larger lateral forces pushing the piles. This matter is solved by using larger sections of piles, with the associated significant increase in the cost of foundations.

Vibration

Longer trackers are prone to suffering from a higher wind load pressure, which can loosen fastenings. 90m long trackers require more frequent torque checking in O&M services.

Use of Land

Longer trackers require a larger area of land, which can result in the installation capacity being reduced due to a limited extension of land.

Energy Power

Longer and heavier components require more energy consumption by the system's motors.

Strengthening the tracker structure increases the cost per MW of the plant, since the solution includes the installation of a **larger quantity of components** and adds **more weight** to the tracker.

4.5 Module Pressure Analysis

STOW STRATEGY DEFINITION

The wind pressure coefficient applied to the module surface is increased with tilt angles and affect the stow strategy of the tracker.

Large-format modules might result in lower mechanical tracker performance. The **stow strategy** of the system is critical to this aspect. Primarily 1P, but also 2P trackers might suffer an increase of pressure on modules due to a high tilt angle at stow position.

Higher allowable pressures are guaranteed for 2P at low tilt angles and 1P at high tilt angles for extreme wind conditions. Trackers experience **higher external dynamic loads** from modules exposed to significant wind pressure at a high tilt angle. At the same time, they also encounter **less aeroelastic instability** due to torsional vibration.

Therefore, a critical aspect of tracker designing is to balance dynamic loads and aeroelastic instability.

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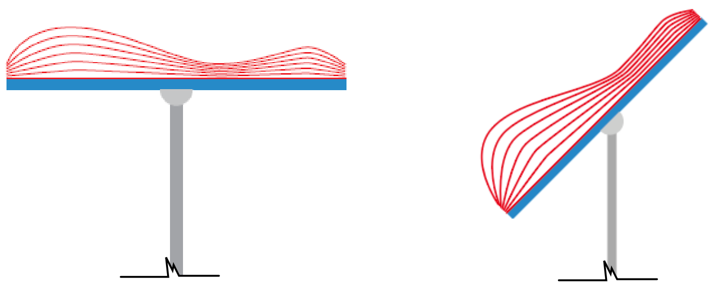


Image 17: Pressure on modules at different tile angles

Image 18: Agile 1P (left) and Vanguard 2P (right) stow angle positions

Wind load pressure on the module's surface is calculated by multiplying wind tunnel pressure coefficients by the standard wind pressure already calculated in the project.

Pressure on the module surface calculation is obtain by considering wind and pressure parametres simultaneously. On the other hand, the snow factor can be excluded in the pressure assumption for the lower surface of the module calculation.

In order to define **allowable module pressures**, several calculations are performed, according to the processes shown below, as established in the relevant Benchmark Regulations for the PV sector.

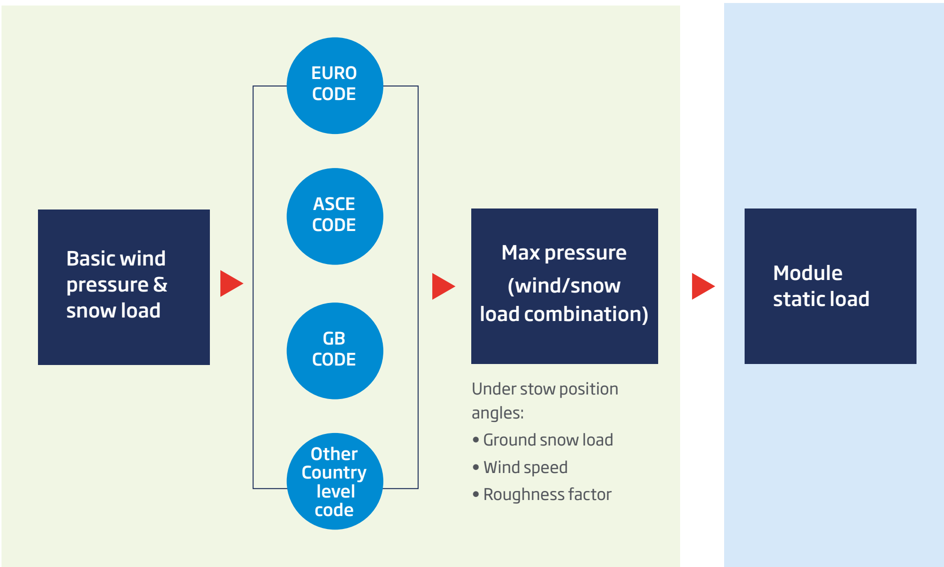


Image 19: Procedures for converting basic wind/snow load pressure to design load on module

The "triangular" pressure distribution for the 1P configuration divides the pv module into **4 zones** with different pressures.

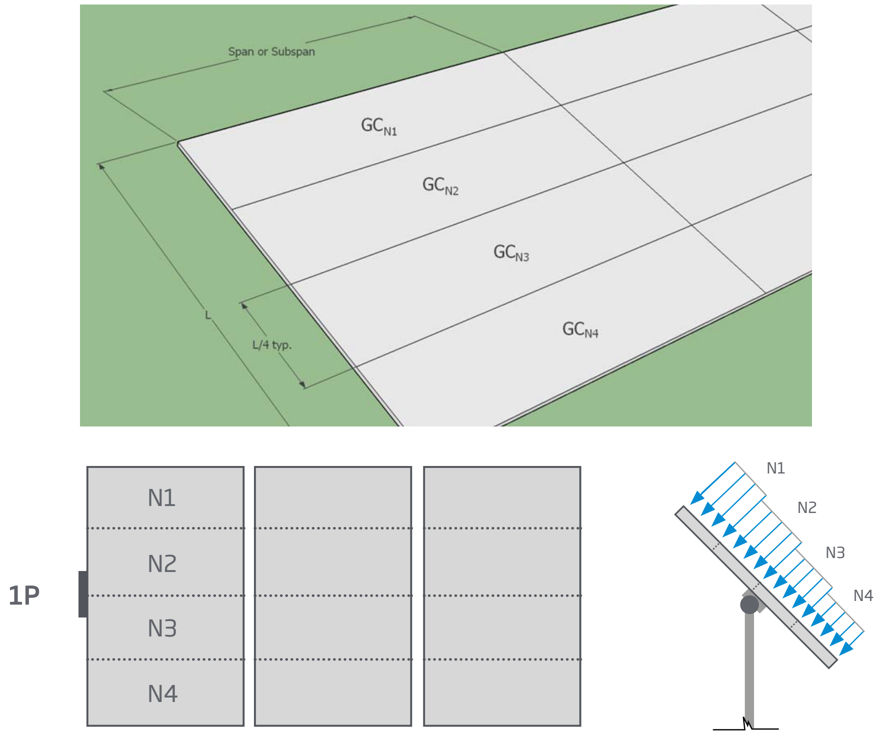


Image 20 (1&2): Wind pressure distribution on module in 1P configuration

The pressure distribution on the PV module in 2P trackers is rectangular.

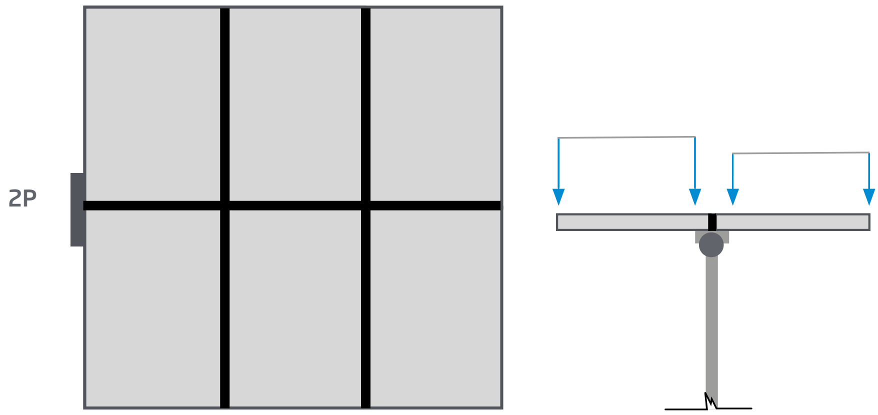


Image 21: Wind pressure distribution on module in 2P configuration

5

Wind Tunnel Test

5.1 Pressure Model Wind Tunnel Research

Wind pressure analysis resulting from tunnel testing together with module pressure must be studied to understand the **quantitative impact of wind loads** on tracker stiffness and stability and therefore, to configure a design according to these parameters.

Tracker length is established on the basis of the clients' requirements.

Image 22: CPP laboratory

Analysis is carried out to obtain full-scale peak responses by combining the effects of wind loads, gust wind loads, and inertial wind loads in order to increase the provided equivalent static wind load with resulting **DAF** (Dynamic Amplification Factors)

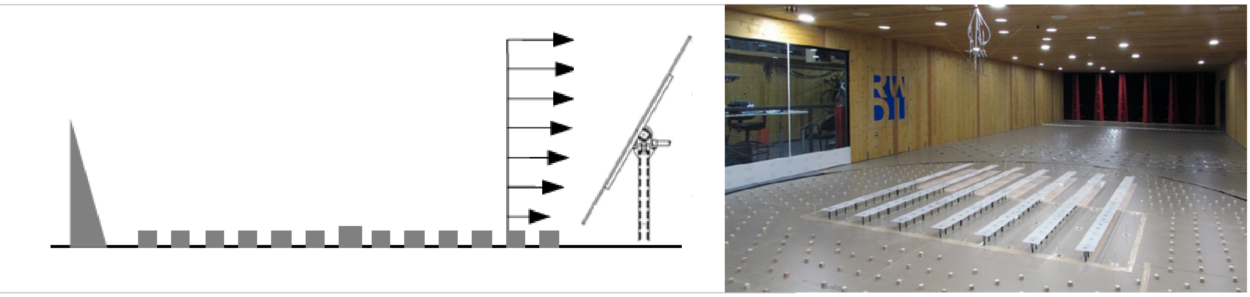


Image 23 (1 & 2): Prototype test for static coefficients and DAF factors

STATIC WIND LOAD COEFFICIENT

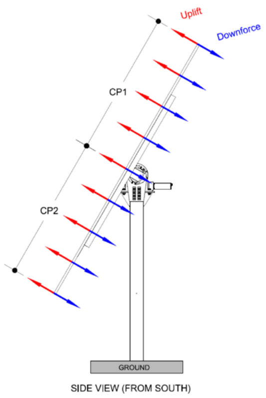


Image 24: Uplift and downforce diagram

The uplift and downforce cases are presented as distributions on either side of the chord, shown as CP1 and CP2 in the following diagram.

Negative CP, or “uplift”, is defined to act outward to the upper PV surface, and positive CP, or “downforce”, acts inward. This definition is consistent with the **ASCE 7 Standard**. In the case of torque or moment (CM), the coefficients correspond to the integrated torque over the full chord length and the worst-case absolute value with rotational direction has been provided.

These coefficients do not include any allowance for dynamic (or inertial) effects assuming the system component being designed is infinitely stiff. The static coefficients should be multiplied by the appropriate dynamic values.

DYNAMIC WIND LOAD COEFFICIENT

The tabulated static wind loading coefficients do not include an allowance for resonant (or inertial) loading. Dynamic (or inertial) wind load factors (DFs) to increase the provided static coefficients have been determined based on the amplification of the fluctuating wind loads due to wind buffeting.

DETERMINATION OF FULL-SCALE WIND LOADS

To obtain full-scale wind loads from the provided coefficients, the following equations should be used.

ASCE 7 Installations

$$F_N = q_z \cdot (CP_{Static} \cdot DF) \cdot A$$

$$M_{torque} = q_z \cdot (CM_{Static} \cdot DF) \cdot A \cdot L$$

Eurocode Installation

$$F_N = q_b \cdot c_e \cdot (CP_{Static} \cdot DF) \cdot A$$

$$M_{torque} = q_b \cdot c_e \cdot (CM_{Static} \cdot DF) \cdot A \cdot L$$

Where:

$\mathbf{F_N}$ and $\mathbf{M_{torque}}$ are normal force and moment around the torque tube;

$\mathbf{q_z}$ is velocity pressure evaluated at height z at the centroid of the area, **A**, for selected exposure as per **ASCE 7** procedure (i.e., constant below 15 ft and Kd = 0.85);

$\mathbf{q_b}$ is basic velocity pressure as per Eurocode procedure;

$\mathbf{c_e}$ is exposure factor at height z at the centroid of the area, **A**, for selected exposure as per Eurocode procedure;

A is either the area associated with **CP1**, **CP2** coefficients or the full chord **CM** coefficients for the various tributary lengths

L is the chord length;

"Static" coefficients provided to **TrinaTracker**;

"DF" are dynamic factors provided to **TrinaTracker** and apply with the sign that yields the worst-case loading.

Body (pressure) coefficient: as shown in the figure below, at the same wind speed, the pressure of the tracker at different angles (body) is distributed differently, and the ratio of the pressure to the basic wind pressure (as shown in the figure below)

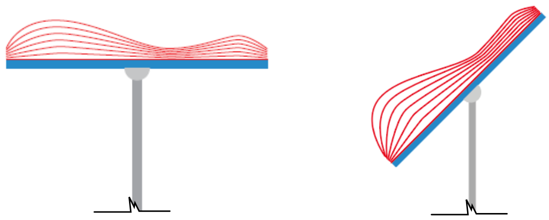


Image 25: Wind distribution at different angles

$$CP = GC_N = C_{p,net} = \frac{P_{net}}{\frac{1}{2}\rho \cdot V^2 \cdot K_{z\,ASCE}}$$

$$CM = \frac{T_{torque}}{\frac{1}{2}\rho \cdot V^2 \cdot K_{z\,ASCE} \cdot A \cdot L}$$

Under the condition of continuously varying wind speed, the pulsating wind is coupled with the system structure to produce resonance. The system with different stiffness will produce magnified wind load.

Pressure wind tunnel testing is performed on a rigid tracker model. The data obtained is for static wind load and dynamic wind load. The pressure and moment coeffients are calculated using the static wind load.

On the other hand, dynamic wind loads are used to define the **Dynamic Amplification Factors** (DAF) as shown below:

$$DAF = \sqrt{1 + \frac{\pi}{4\zeta} \frac{f\,s(f)}{\sigma^2}}$$

f System inherent frequency

ζ Damping ratio

$\frac{f\,s(f)}{\sigma^2}$ Normalized spectral density at the natural frequency (f).

The total peak loading, including the **DAF**, can be described in general terms using the following expression which includes the mean, background ("B"), and resonant ("R") components.

$$P_{total} = P_{mean} \pm P_{rms} \cdot \sqrt{(g_{Bp})^2 + (g_{Rp})^2 \cdot (DAF^2 - 1)}$$

A commonly-used expression for estimating the resonant peak factor, g_{bp}, can be found in Davenport[2] for a response that has a closely **Gaussian** probability distribution:

$$g_R = \sqrt{2 \ln(\nu T)} + \frac{0{,}577}{\sqrt{2 \ln(\nu T)}}$$

where v is the cycling rate, often conservatively taken as the natural frequency;

T is the time interval over which the maximum value is required

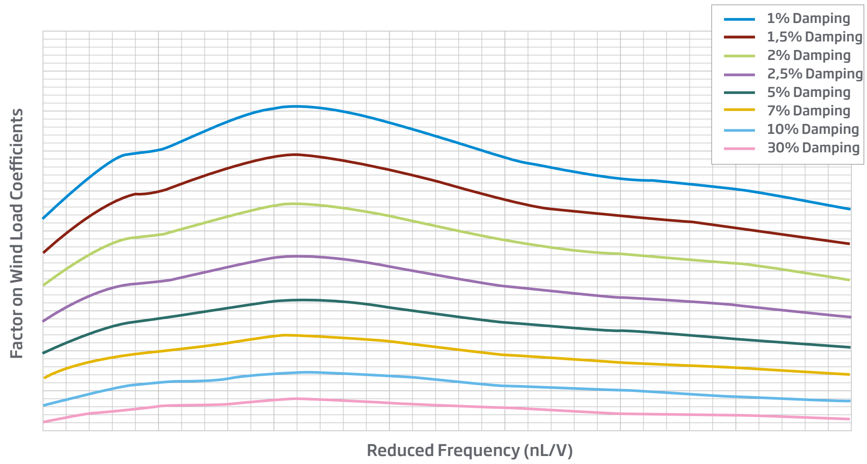


Image 26 - Chart : Dynamic amplification factors

Additionally, for the definition of the **DAFs** different tracker modes are defined and a free vibration test (fvt) is performed.

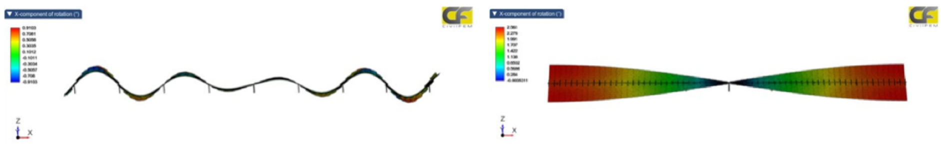


Image 27: Tracker modes

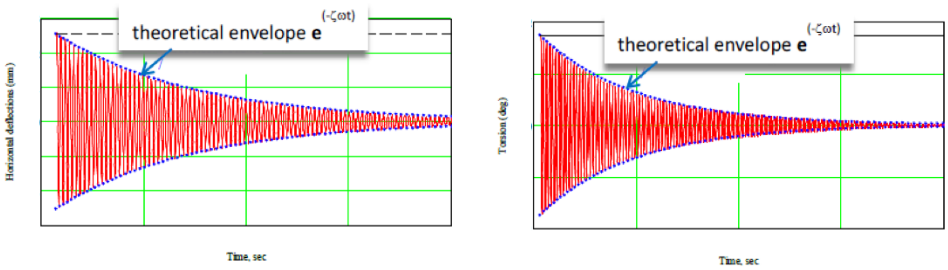


Image 28- Chart : Tracker modes

5.2

2D Sectional Model Test & Numeric Models

This test called "**Recogn Methodology**", was designated by **RWDI** to be performed exclusively on the **Vanguard 2P** series.

The test is implemented to define the tracker's **self-excited** forces by measuring aerodynamic derivatives, static aerodynamic forces and moment coefficients. These parameters are critical to execute the **3D Flutter Analysis** and the **3D Buffeting Response Analysis** to calculate wind loads.

Tracker stability and dynamic wind loading including self-excited forces is investigated through aeroelastic wind tunnel research.

A **Sectional Model** of the tracker representing a typical section of the tracker at full scale with a rigid model. The model is designed based on the geometry, mass, mass moment of inertia, and dynamic data provided by **TrinaTracker**.

The Sectional Model was mounted on a spring suspension system. The suspension system was built into support walls with the springs and damping components shielded from the wind by fairings at the start and end of each wall. The spring suspension system allowed torsional motions to be simulated and measured by means of laser displacement transducers. The drag, lift and moment loading on the tracker section were measured with embedded high precision load cells.

Damping was added to the system by magnetic eddy current damping devices installed on the rig within the shielded wind tunnel walls.

Image 29 - Video: 2D section model test. **RWDI** Lab

Dynamic tests in smooth flow were conducted at different tilt angles to measure the aerodynamic derivatives.

During each test, the wind speed was gradually increased in small steps and torsional motions were recorded. Multiple free-vibration samples were taken at each wind speed increment to refine the estimate of the aerodynamic derivatives.

The suspension rig was also used to measure the static force and moment coefficients where motions of the model were mechanically prohibited.

The 2 D sectional model test defines the aerodynamic derivatives.

In the case of structures susceptible to vertical and torsional motions, such as long-span, the two degree-of-freedom aerodynamic derivatives refer to the Hi* and Ai* coefficients in the self-excited aerodynamic forces and moments.

$$L_{se} = \frac{1}{2}\rho U^2 L \left[kH_1^* \frac{h}{U} + kH_2^* L \frac{\alpha}{U} + k^2 H_3^* \alpha + k^2 H_4^* \frac{h}{U} \right],$$

$$M_{se} = \frac{1}{2}\rho U^2 L^2 \left[kA_1^* \frac{h}{U} + kA_2^* L \frac{\alpha}{U} + k^2 A_3^* \alpha + k^2 A_4^* \frac{h}{U} \right],$$

Where:

$\mathbf{L_{se}}$, $\mathbf{M_{se}}$ are the self-excited lift force and moment per unit length, respectively;
k is the reduced frequency k = 2πf L / U;
h, **α** are the vertical and torsional deflections of the structure, respectively, and over dot represents derivatives with respect to time;
L is the representative width (typically the chord length);
ρ is the air density (1.225 kg/m^3); and
U is the mean wind speed at the structure height.

The **aerodynamic derivatives** are functions of the reduced frequency and reduced wind speed

The **peak rotations** and **peak moments** are obtained to have a more flexible method for obtaining the peak moments considering aeroelastic effects on all tracker rows, "dynamic" wind loading factors based on the buffeting approach are provided.

Tracker stability and dynamic wind loading including self-excited forces is investigated by using **RWDI's 3D Flutter Analysis** and **3D Buffeting Response Analysis Methods**.

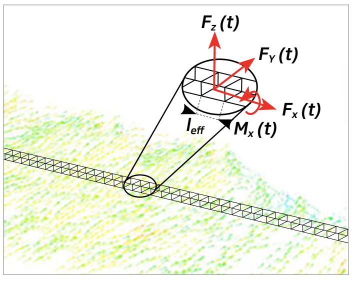
The aerodynamic derivatives define self-excited forces and moments used for:

3D FLUTTER ANALYSIS

3D Flutter Analysis obtains dynamic actions of the wind caused by aerodynamic instability phenomena.

To assess the aerodynamic stability of the tracker, **RWDI's 3D Flutter Analysis procedure** was applied.

This analysis allowed the onset of flutter to be predicted considering the mean wind profiles, and the overall dynamic and aerodynamic tracker properties.



The motion equation of a body subjected to the dynamic action of wind is given by:

$$[M]\{Z\} + [C]\{\dot{Z}\} + [K]\{Z\} = \{F\}_{SE} + \{F\}_{BUFF}$$

Vector $[M]$, $[C]$ and $[K]$ correspond with the mass, damping and stiffness matrix of the system, and $\{F\}_{SE}$ & $\{F\}_{BUFF}$ represent the self-excited and the buffeting forces.

Image 30: Equation of motion used for 3D Flutter analysis

The **predictions** from the **3D Flutter Analysis** include the variation of structural frequency and total structural damping as a function of wind speed. The fluid-structure interaction between the wind and the structural dynamics leads to changes in the frequency and damping due to the addition (or subtraction) of aerodynamic stiffness and damping, respectively. **An aerodynamic instability** is identified at the wind speed where the total damping in the system goes negative and this critical wind speed has been identified over a range of static tilt angles. **TrinaTracker** designs the structures below the critical wind speed during operating or stow conditions.

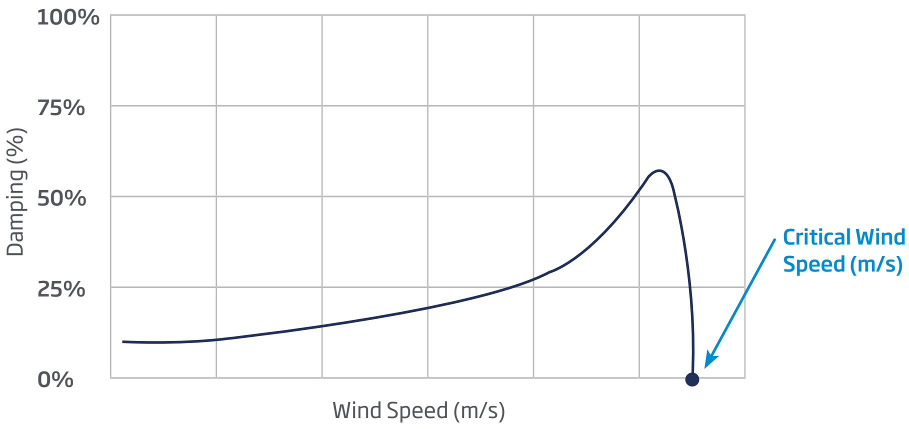


Image 31 - Chart: Critical wind speed according to the damping ratio

Tracker instability is assessed at each of the tilt angles by implementing **aerodynamic derivatives**. The use of numerical methods defines the chord length and the natural frequency of the tracker. **Critical wind speed** occurs when the damping turns into negative values.

3D BUFFETING RESPONSE

3D Buffeting Response Analysis combines mean, gust and inertial wind loads to obtain an equivalent static design wind load.

The **3D Buffeting Response** of the structure is determined through simulation of a 1-hour statistically stationary wind event considering all the expected gust structure and durations for open terrain conditions.

Input parameters include static aerodynamic force and moment coefficients, mass, polar moment of inertia, tracker dimensions, modal frequencies, mode shapes, structural damping, and wind turbulence properties.

The global response of the structure results from the integration of the fluctuating turbulent flow field over the length of the tracker.

TrinaTracker obtains the peak rotations and peak moments of the structure considering aeroelastic effects on all tracker rows, "dynamic" wind loading factors.

These coefficients should be combined with the static wind load coefficients from the pressure approach.

The sectional model technique described in this report is the ideal approach to assess the wind-induced buffeting responses of a single tracker row (or the first leading row in an array) for normal wind azimuths where the **self-excited** forces are most dominant. However, it is limited when it comes to assessing different wind azimuths and multiple rows within an array. This can be done for a specific system through full aeroelastic model research, which is beyond the current scope.

5.3 Full Aeroelastic Model Test

The full aeroelastic model test is performed on 1P and 2P trackers. With regard to 2P configuration, the full **aeroelastic test confirms the 2D sectional model test results**. On the other hand, the same test is executed to define the stow position strategy for 1P trackers.

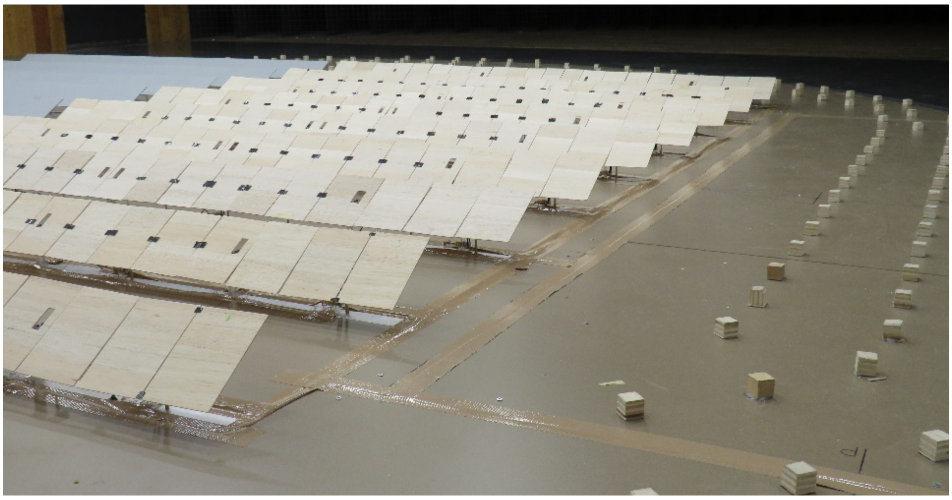


Image 32: Prototype for full aeroelastic model test. Source: **RWDI** Lab

3D Aeroelastic Model Testing assesses the **aerodynamic stability** and **wind-induced buffeting responses** of the tracker.

For the design of the individual trackers, the models are essentially lumped mass dynamic models where the torsional stiffness properties of the torque tube are provided by a scaled "spine" within the model.

The exterior geometry and mass properties of the panels are modelled using "shells" that are mounted at discrete locations along the structural spine. The shells were built by hand in segments, primarily made from balsa wood and securely fastened to the structural spine which was made from spring steel.

These segments simultaneously account for the distribution of **mass moment** of inertia (MMI) along the tracker span while maintaining accurate geometry to ensure the proper distribution of the aerodynamic forces and moments.

Image 33: Prototype for the 2D Sectional Model test

Once the physical model was built, the torsion mode frequencies were measured experimentally for each row and compared against the target values.

Full Aeroelastic Model results are torsional moment and the critical wind speed that defines stow position . This results **validate the data** obtained from the 2D Sectional Model Test and Numerical Tests.

6

Strategic Design Solutions

6.1 Structure Design & Validation

Upgrading trackers to accommodate large format modules requires numerous structural design adaptations to achieve system reliability and optimum energy generation at all wind speeds

The described static, dynamic and aeroelastic analysis together with the module pressure analysis provide multiple calculations with various coefficients (including "DAF"), which enable the systems to comply with **EURO CODE or ASCE Standards**. Data on forces and torsions is essential for defining tracker design.

Therefore, upgrading trackers to accommodate large format modules requires numerous structural design adaptations to achieve system reliability and optimum energy generation at all wind speeds.

The upgrading of tracker design considers several **strategic solutions**:

STIFFER TORQUE TUBE

Larger modules mean higher torsional moments on the tracker rotational axis. The torque tube of the upgraded tracker includes a larger cross-section, increased thickness and strength. A sturdy torque tube brings higher natural frequencies to the system avoiding dynamic effects. The new design **increases the torque tube dimensions by 28%**.

The design of the most complex elements of the tracker is configured with the implementation of **"The Finite Element Method."** This analysis identifies those areas of stress concentration that need a change in thickness or reinforcement.

The Finite Element analysis is not sufficient to validate the modifications made in the trackers since **FEM calculations** are often done over an isolated part of the system.

Therefore, the results that represent the impact of deformations in the other parts of the structure exposed to loads are not 100% realistic. Consequently **full-size load tests** are performed to obtain this type of data.

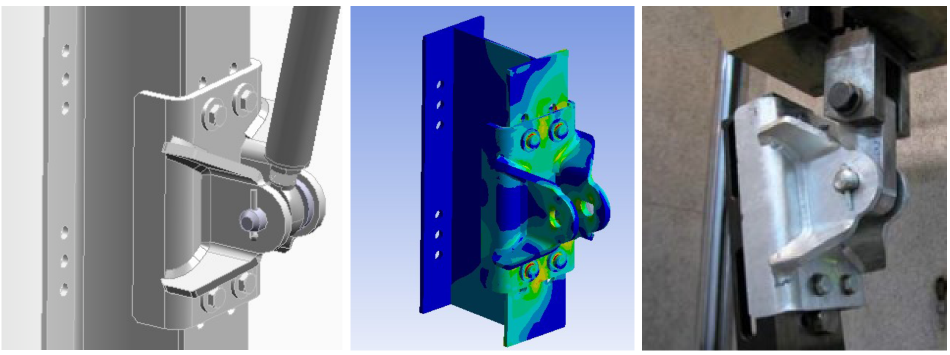


Image 34 (1,2 &3): Linear actuator base

MULTI-DRIVE SYSTEM

The torsional locks and the torque tube in 2P configuration reduce torsional spans, increase natural frequencies and damping and prevent torque tubes from twisting. Longer trackers with 1P and 2P configurations lower torsional stiffness. Therefore, **multi-drive systems** are adopted to effectively reduce **torsional loads** from **buffeting**.

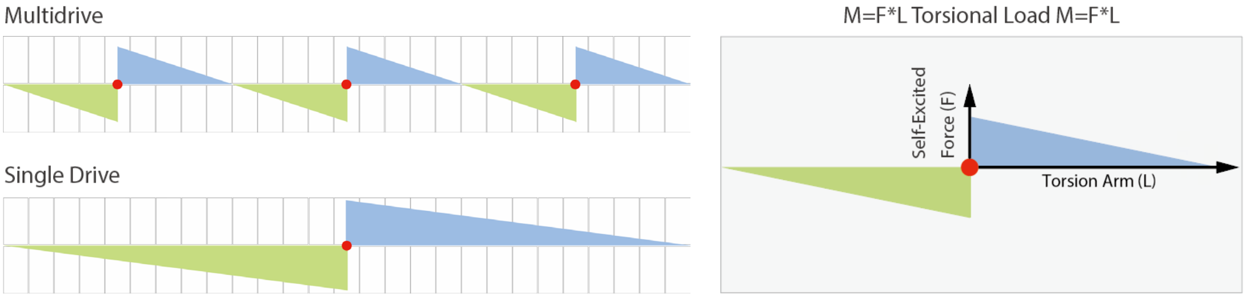


Image 35 (Chart): Vanguard 2P design overview

TrinaTracker assembles experimental trackers in its **own facilities** to verify the adequate performance of the system, test multi-actuators, and ensure that energy consumption and load tests are performed under different conditions.

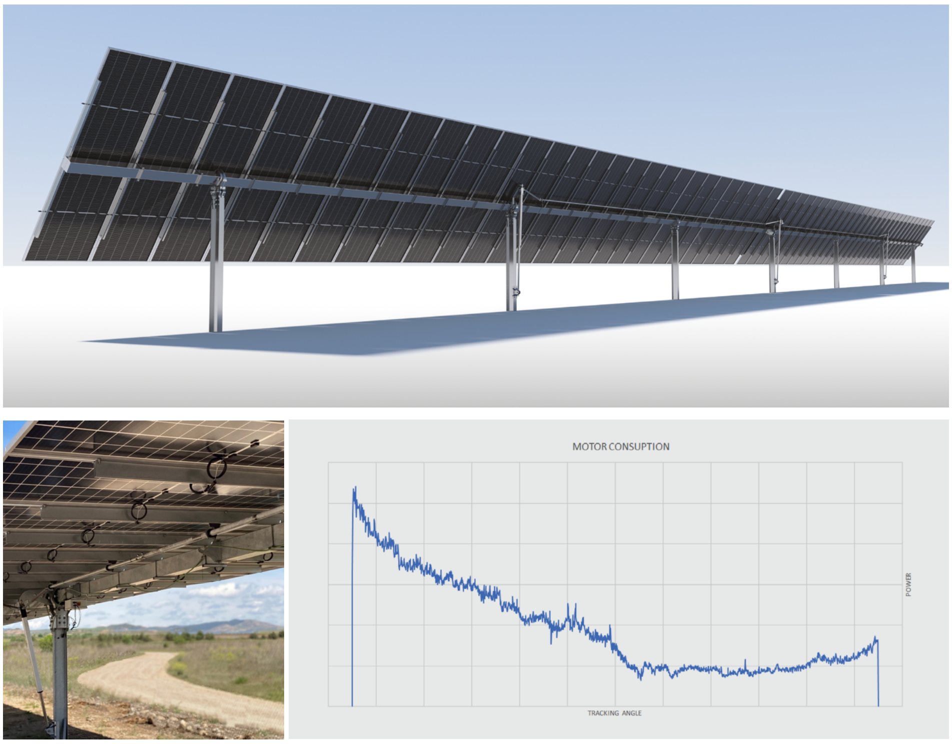


Image 36: Tracker testing under beta site conditions

OPTIMIZED PURLINS

Critical challenges in pv installations include achieving optimal combinations between mechanical loading and large-format modules.

The use of **purlins** in solar trackers provides **extra rigidity** to the modules. With the introduction of large-format modules and 2P configurations, purlins are redesigned to **optimize steel usage**.

Dynamic effects are also well known for causing purlin fastenings to torque tubes to become loose due to vibrations. **Sturdy purlins** prevent modules from micro-cracking and loosening.

TrinaTracker assembles experimental trackers in its own facilities to verify the adequate performance of the system, test multi-actuators, and ensure that energy consumption and load tests are performed under different conditions.

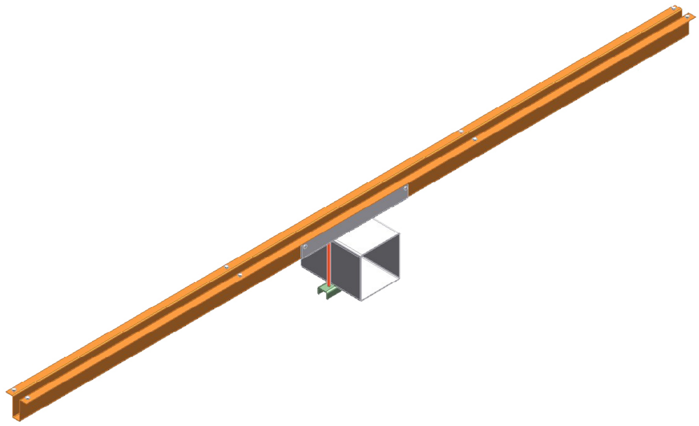


Image 37: Reinforced purlin design

OPTIMISED POST

1P and 2P tracker components are optimised to reduce the number of posts installed per tracker. The posts used in upgraded trackers are designed with **larger cross-sections** to avoid problems caused by ramming, such as localised impacts or twisting. A reduction in number of posts per tracker minimises the risk of **soil-related issues**.

MODULE TESTING

Module resistance is tested to substantiate the pressure supported by modules under different tilt angles and comply with **IEC 61215-2 Standard**. Critical input is gathered from the pressure and suction hypothesis.

6.2 Stow Strategic Solutions

Different stow management strategies are defined, taking into consideration the configuration of the tracker, location of the project or meteorological conditions of the site.

Different stow strategies are defined, taking into consideration the configuration of the tracker, location of the project or meteorological conditions of the site.

6.2.1 Wind Stow Strategy to Mitigate Negative Pressure on Module

In the 1P configuration, a the stow position at high tilt angle has been chosen. This position **minimises the dynamic effects** despite high wind pressure on modules.

In the 2P configuration the stow position is set at a low tilt angle. In this position the dynamic behaviour governs the design and the maximum pressure on the PV panels is minimized. To avoid any aeroelastic instability, **multi-drive system** is installed. The multi-drive system fixes the torque tube in different points multiplying the torsional frequency by three compared to the traditional one-fixed point 2P configuration.

Image 38: Snow load

Image 39 - Video: Snow Storm

6.2.2 Snow Stow Strategy to Mitigate Positive Pressure on Module

Solar installations are expanding in areas where snow in abundant and frequent for several months of the year, like, for example, the regions located in Northern Europe and the American North.

Therefore, snow load pressure on modules becomes the greater challenge to overcome and a critical factor that defines tracker design.

Potential issues triggered by snow loads are mitigated with the integration of snow sensors as part of the sensor package which, connected to the NCU, governs tracker behavioiur and movement toward the stow position when any of the sensors is activated due to severe weather conditions, avoiding unnecesary risks for the system.

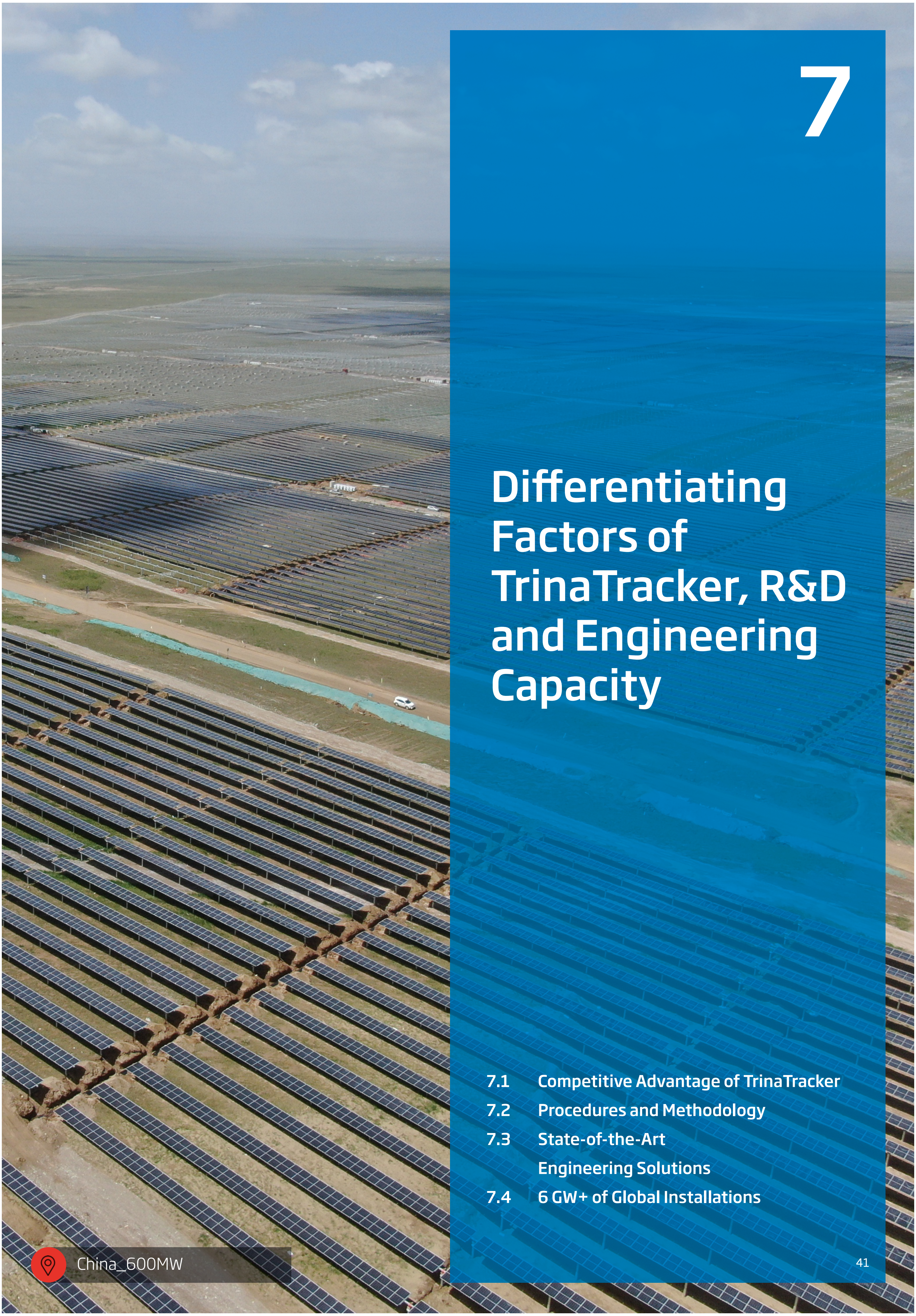
In the case of snow cumulation detection by snow sensors, the alarm will be activated and trackers will rotate accordingly to avoid snow accumulation.

The strategies are focused on the correct rotation of the trackers to avoid snow accumulation.

6.2.3 Hail Stow Strategy to Mitigate Damages

The impact of hailstorms on modules becomes a significant problem in certain regions in China and the US, for example. The consequences of hailstorms could be detrimental to PV installations.

Alarm systems with hailstorm sensors are integrated in the project designs. The sensors communicate with the **NCU**, which will automatically activate the trackers into the angle established for hailstorm stow position. The stow position can be also activated manually at the **operator's criteria**.



7

Differentiating Factors of TrinaTracker, R&D and Engineering Capacity

7.1 Competitive Advantage of TrinaTracker

TrinaTracker, a business unit of **Trina Solar Ltd.** (SHA:688599), is a global solar tracker technology leader focused on providing "state-of-the-art" design solutions tailor-made to any terrain characteristics and weather conditions.

The company has more than 6GW of solar trackers deployed across 40 countries in which they accurately adapt the solar systems to each site's features. **TrinaTracker Agile 1P** and **Vanguard 2P** stand out in the market for their reliability, optimised design and minimum operation and maintenance requirements.

The trackers' compatibility with ultra-high power modules has been reported by DNV. Furthermore, **Agile 1P** and **Vanguard 2P** have been subjected to static, dynamic and aeroelastic loads through the most extensive tunnel test implemented in the solar industry and perform by leader wind engineering consultants **CPP** and **RWDI**.

TrinaTracker is entirely focused on quality and innovation to provide its clients with high-technology solutions that achieve the highest energy yield and lowest **BOC** costs and **LCOE**.

About Trina Solar

Founded in 1997, **Trina Solar** is the world-leading PV and smart energy total solution provider. The company engages in PV products R&D, manufacture and sales; PV projects development, EPC, O&M; smart micro-grid and multi-energy complementary systems development and sales; and energy cloud-platform operation.

In 2018, **Trina Solar** launched the Energy IoT brand, established the Trina Energy IoT Industrial Development Alliance and leading enterprises and research institutes in China and around the world, and founded the New Energy IoT Industrial Innovation Center. With these actions, **Trina Solar** is committed to working with its partners to build the energy IoT ecosystem and develop an innovation platform to explore New Energy IoT, as it strives to be a leader in global intelligent energy. In June 2020, Trina Solar listed on the STAR Market of the Shanghai Stock Exchange.

For more information, please visit **www.trinasolar.com**.

Competitive Factors

Own R&D & Engineering Department

Team of more than **50** experienced and highly qualified engineers

Consolidated expertise in modelling, calculation and engineering design

Extensive know-how of solar industry technology and markets

6 GW of plants where tracker design is tailor-made to meet the site characteristics and clients' requirements

Trackers installed in more than **40 countries**

In-house resources to carry out geotechnical design, structural design, FEM analysis, physical testing, software and hardware design, detailed project design, research and development of products.

Work partnership with leading wind engineering consultancy companies (**RWDI** and **CPP**)

State-of-the-Art **engineering** design

Designed technology that complies with the highest **European and US standards** (IEC62817 and UL3703 Certifications respectively)

RWDI

cpp WIND ENGINEERING & AIR QUALITY CONSULTANTS

DNV

sbp schlaich bergermann partner

7.2 Procedures and Methodology

TrinaTracker implements rigorous and meticulous **procedures and methodology** to guarantee the correct functioning of the trackers and avoid potential failures.

The company not only provides solutions to problems but makes the most of any incident by considering it as an opportunity to add value to the trackers.

PROBLEM WE SOLVE	Method	Value
How new tracker is compatible with big modules	Compatible design of module tracker	Reliable and bankable company and product
Complex terrain and harsh application environment	Unique spherical bearing & Multi-drive system	
Non-bankable company balance sheet	Top and strict WTT Lab Tests	
	Solid company balance sheet	
PPA is declining fast	Intelligent Algorithm	Higher Power Generation
No efficient technology to improve yield	Shading mitigation engineering design	
PPA is declining, investors need to maintain IRR	Longer strings/less piles	Lower System Cost
System cost reduction slows down	Fast installations	
O & M costs are rising due to labour costs and complex Sites & environment	SCADA O&M platform	Smarter O&M Platform
Traditional O & M efficiency is low		
Delay of delivery due to non-integrated delivery	Integrated one-stop delivery of module and tracker	High delivery efficiency

Image 40 -Table: TrinaTracker's problem solving methodology

FAILURE AND EFFECTS MODAL ANALYSIS (FEMA)

Failure mode and effects analysis is the process of reviewing as many components, assemblies and solar tracker subsystems as possible to **identify potential failure modes** in a tracker system and their causes and effects. For each solar tracker component, the failure modes and their resulting effects on the rest of the system are recorded in a specific **FEMA worksheet**.

A successful FEMA activity helps us to identify potential failure modes based on experience with similar solar trackers produced in the past.

Trinasolar — **FEMA DESIGN** — **TrinaTracker**

Cod:
FEMA:
Date:
Sheet

Element: — Design responsible — By:
Customer: — Launch date — Date 1st rev — Date 2nd rev
Analysis team:

Function	Potential failure mode	Potential failure effect	Severity	Potential failure cause	Ocurrency	Current controls	Detection	NPR	Corrective actions	Person Responsible and date	Results: Submitted actions	Results: Severity	Results: Ocurrency	Results: Detection	Results: NPR
Function 01	Failure in function 01	Effects of the failure 01	8	Cause of the failure 01	1	Visual on site	1	8							
Function 02	Failure in function 02	Effects of the failure 02	8	Cause of the failure 02	1	Visual on expedition	1	8							
Function 03	Failure in function 03	Effects of the failure 03	8	Cause of the failure 03	1	Prototype test	2	16							

Image 41 - Table: Reinforced purlin design

Failure Factures to be Measured

Severity

Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, system damage and/or time lost to repair the failure.

Occurrence

The likelihood of the failure occurring.

Detection

Awareness of failure mode by maintainer, operator or built-in detection system, including estimated dormancy period (if applicable).

RPN

Risk Priority Number.

SIGN, CAUSE, REMEDY AND ACTION (SCRA)

SCRA is a **problem-solving** method that follows a logical **step-by-step** approach to identify the causes of the problem and propose actions to prevent recurrence.

SCRA

S — **Sign**

The 6 W's: "what, who, when, where and how". Purpose: Establish the "focus" on the analysis.

C — **Cause**

"why" Purpose: Look into the root of the problem.

R — **Remedy**

Search for all possible solutions to the symptom. Purpose: Define corrective, preventive or even proactive measures.

A — **Action**

Relate the **"Remedies"** to more concrete actions, so that they can be planned, indicating a description of the measure **("what")**, the person responsible for implementing it **("who")** and the execution deadline **("when")**.

QUALITY DESIGNING TOOLS

The company adopts key tools for **quality control** that enable efficient data communication and visual representation, leading to an accurate, assertive, and fluid decision-making process.

The tools operate vertically across all departments and business areas existing in the company.

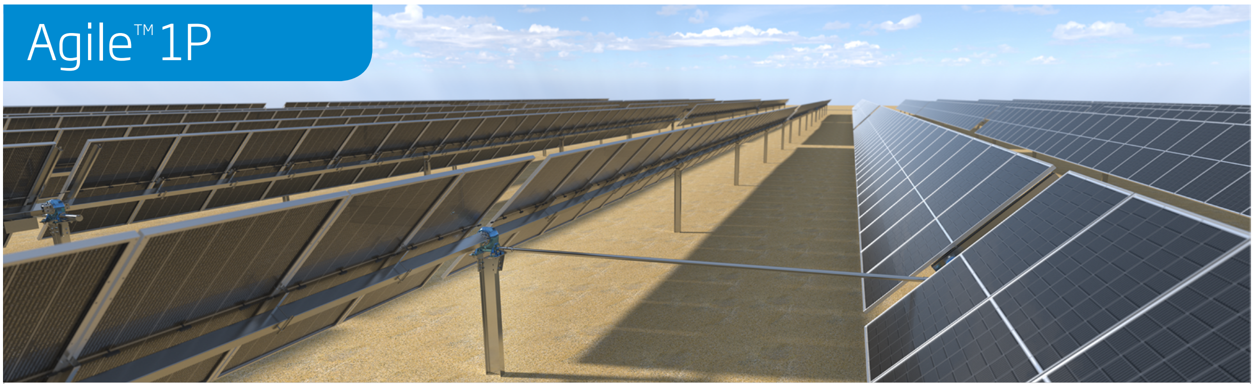
Image 42: Definitions of 7 Tools

7.3 State-of-the-Art Engineering Solutions

Vanguard™ 2P

- 2P configuration compatible with ultra-high power modules up to 210 mm wafer size.
- Multi-drive system allows better wind tolerance, high adaptability and stability.
- 120 modules per tracker and up to 4 strings per row. Low voltage optimisation.
- Individual row actuator. Easy access for operation and manteinance activities.
- From 7 piles per row and less than 120 piles per MW.
- Global patented Spherical Bearing allows up to 30% angle adaptability.
- SuperTrack algorithm increses yield gain up to 8%.

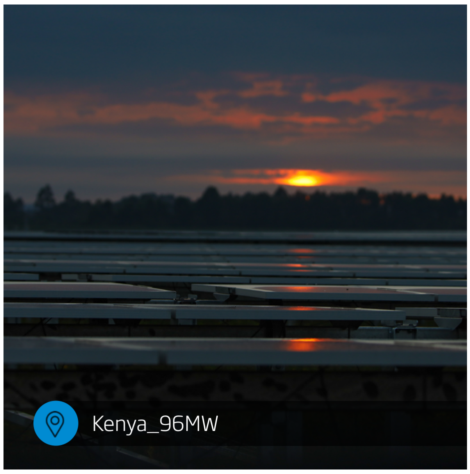
Agile™ 1P



- Individual row actuator. Easy access for operation and maintenance activities.
- 120 modules per tracker and up to 4 strings per row. Low voltage optimisation.
- Dual row actuator. Easy access for operation and maintenance activities.
- Optimised number of components allows low operation and maintenance costs .
- High slope tolerance 20% N/S, 10% E/W.
- Trina Clamp reduces installation time and costs .
- SuperTrack algorithm increses yield gain up to 8%.

7.4 6 GW+ of Global Installations


China_600MW


Kenya_96MW


Chile_33MW

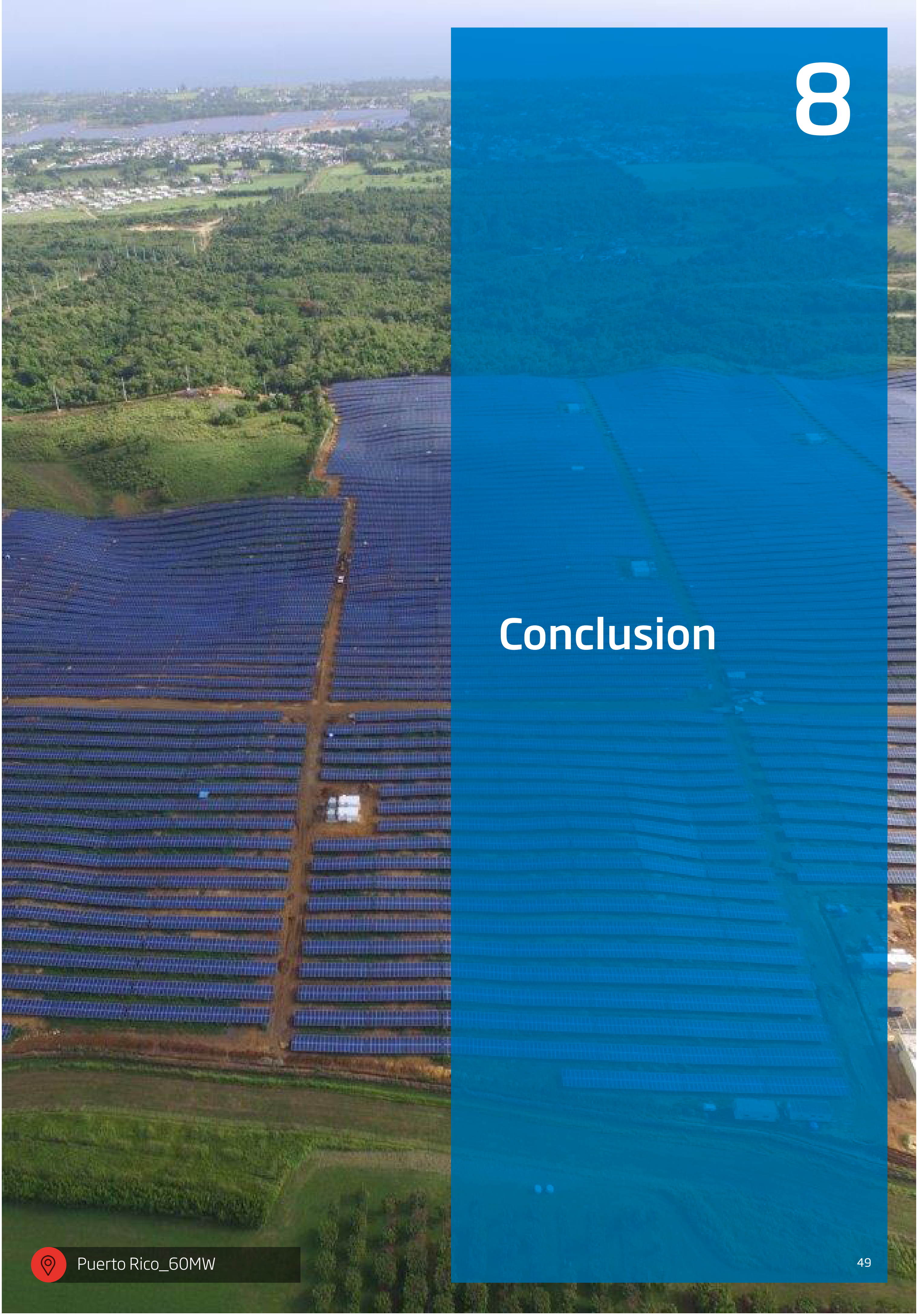

Argentina_32MW


Honduras_40MW


Spain_22MW

8

Conclusion



Puerto Rico_60MW

8 Conclusion

The accuracy of the information extracted from the test is critical to validate the strategic solutions adopted to mitigate wind-related risks and guarantee optimum yield generation and tracker reliability.

The current massive availability of the large-format module in the PV market represents a critical milestone in the solar industry that comes with new **technical challenges** for tracking structures.

Large-formal modules in pv plants benefit from higher energy production and require smaller size terrain for the same installed capacity. However, large-module areas also mean higher wind load pressure that can be detrimental to the **stability** and **durability** of the trackers.

Therefore, one of the most critical challenge in tracker configuration, in this large-format-module-era is the mitigation of **wind-related risks**.

Tracker engineering companies need to react rapidly and efficiently to keep up with industry trends. Consequently, tracker designs need to be upgraded to accommodate large-format modules and reach compatibility.

The new parameters and calculations that define the upgraded designs are crucial to achieving optimum energy production and system reliability. Accordingly, **TrinaTracker**, in partnership with the leading wind consultancy firms **RWDI** and **CPP**, has focused a great deal of its engineering and development resources on performing **wind tunnel tests**. **The tests are carried out in the trackers** under the real and specific wind speed and load pressure existing in each of the installations' sites. The data resulting from the tests determines the system upgrade at the site.

The accuracy of the information extracted from the test is critical for validating the strategic solutions adopted to mitigate wind-related risks and guarantee optimum **yield generation** and tracker **reliability**.

On its path to **grid parity**, the PV industry makes ongoing efforts to optimise power output and system efficiency. The availability of large-format modules has become an essential factor for lowering **BOS** cost and **LCOE**.

As the leading module and tracker manufacturer, Trina has been always well prepared for changes in technology. As part of our product roadmap, we will continuously optimize tracker design to achieve reliable, compatible and smarter.

TrinaTracker

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