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EVALUATION OF HORIZONTAL SINGLE-AXIS SOLAR TRACKER ALGORITHMS IN TERMS OF ENERGY PRODUCTION AND OPERATIONAL PERFORMANCE

Solar RRL - DOI: 10.1002/solr.202300507

Ildefonso Muñoz, Adrián Guinda, Luis Casajús, Gregorio Olivares, Sara Díaz, Ana Gracia
Solar Energy Technologies & Storage Dept. – CENER

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The Energy of Knowledge

The National Renewable Energy Centre of Spain (CENER) develops applied research in renewable energies, and provides technological support to companies and energy institutions.

CENER´s expertise is focused on three main areas:

- Development of **R+D+i projects** for industrial applications.
- Highly skilled **testing services** and certification for components.
- **Technical assistance** and feasibility studies for renewable energy technologies

200 Employees

+100 M€ Investments

+20 M€ Annual Budget

+1000 Clients in +50 countries

- Wind Energy
- Solar Energy Technologies and Storage
- Biomass and Bio-products
- Energy Transition in Cities
- Grid Integration of Renewable Energy

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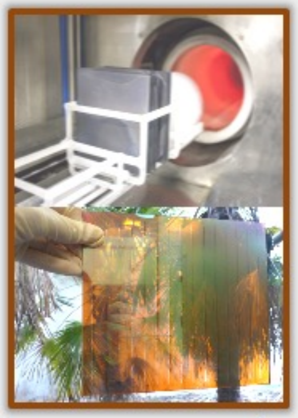
SOLAR PHOTOVOLTAIC - COMPETENCIES IN THE COMPLETE PV VALUE CHAIN



1.SOLAR CELLS, MATERIALS & COATINGS

Solar cell design and manufacturing

Characterization of processes and full solar cell

2. ADVANCED PV MODULE

PV and BIPV element design and prototyping

Glass functionalization

3. PV MODULES & MATERIALS TESTING

PV modules accredited testing laboratory

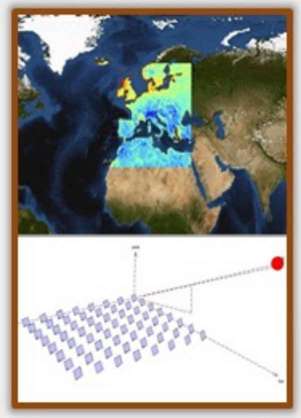
IECEE certification laboratory

Outdoor testing

4. BOS TESTING

Solar Tracker accredited testing laboratory

PV inverter testing, quality & FAT audits

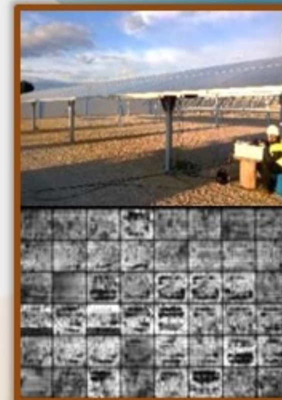


5. PV PLANT DESIGN

Solar resource & energy estimation

Preliminary & PV project finance

Technical advisor



6. PV PLANT BUILDING AND O&M

Commissioning

Full PV plant inspection & diagnosis (aerial EL, IRT, IV curve)

O&M/PV project finance analysis

Solar cell | PV module | BOS | PV power plants

TECHNICAL ASSISSTANCE

CAPACITY BUILDING

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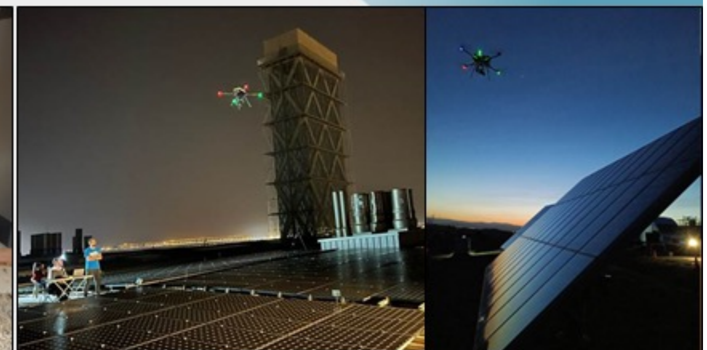
SOLAR PHOTOVOLTAIC - FLAGSHIP ACTIVITIES IN PV COMPONENTS AND INSTALLATIONS

Mechanic load Test-Bench

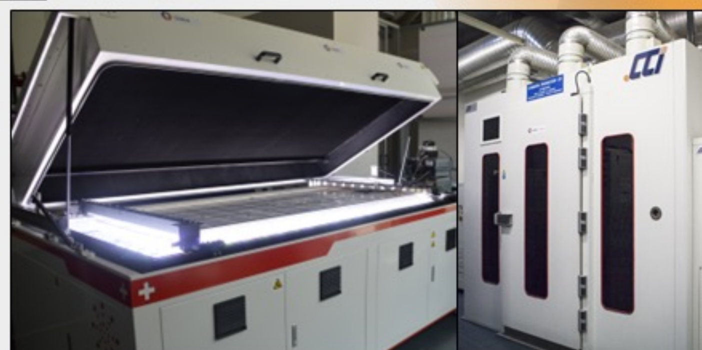
On site research/testing in PV plants



Aerial Electroluminescence

CENER Soiling Test-Bench

CENER experimental PV plant



PV components Lab

PV system simulation tool

Tonatiuh ray tracing for solar energy

SIMPV

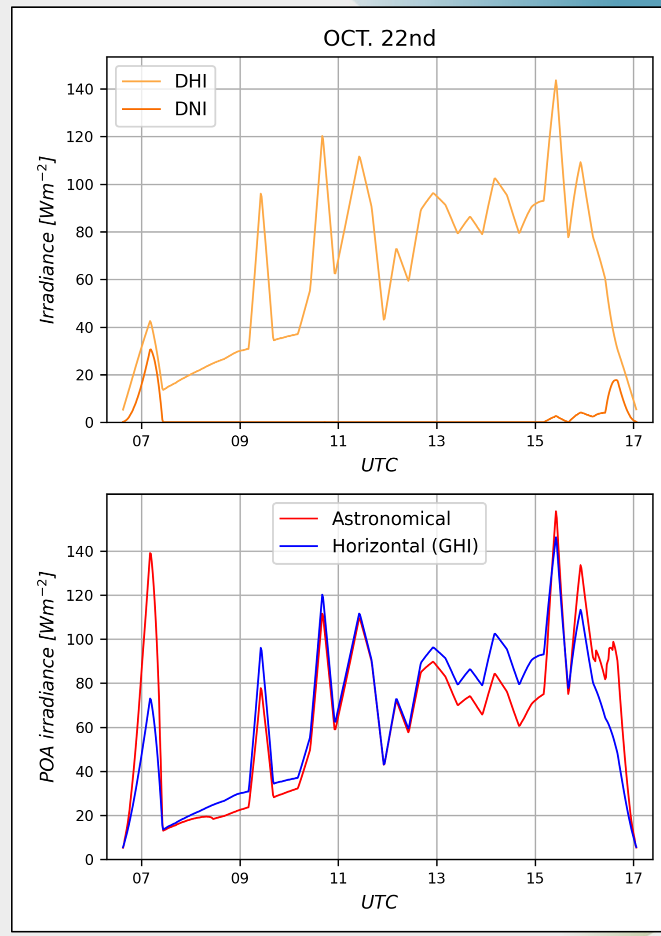
INTRODUCTION & MOTIVATION (1)

CURRENT STATUS

- **Horizontal single axis** → most widely used solar tracker system.
- **Astronomical algorithm with Backtracking strategy** is the most basic and usual algorithm in single axis trackers.

CHALLENGERS & OPPORTUNITIES

- Astronomical algorithm **is not always optimal** → Astronomical ignore sky diffuse and ground reflected irradiation.
- Electronic control system allows an easy implementation of different algorithms.



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INTRODUCTION & MOTIVATION (2)

- Study presented: **In–depth comparative and evaluation** in terms of energy production and operational performance of four solar tracking algorithms.

- Solar tracking algorithms proposed for this study:
  - **ASTRONOMICAL ALGORITHM**
  - **DIFFUSE ALGORITHM**
  - **DIFFUSE+NOWCASTING ALGORITHM**
  - **ANALYTICAL ALGORITHM** (new development by CENER)

- Comparison based on **high temporal resolution TMY (1 minute)** considering:
  - **Mechanical effects** on tracker (non-continuous movement, turning speed)
  - **Disposition of PV modules** on the solar tracker

METHODOLOGY – SOLAR TRACKER ALGORITHMS (1)

Astronomical Algorithm

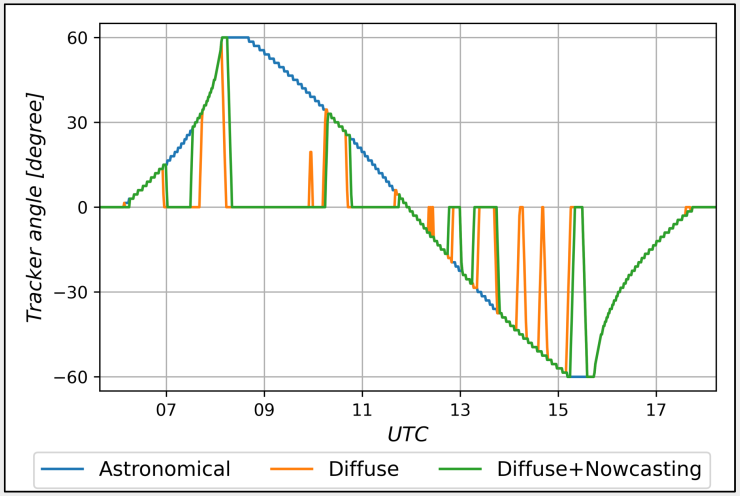
- Maximize beam component.
- Irradiance loss on cloudy days (GHI>G_{POA}).

Diffuse Algorithm

- Evaluate between astronomical/horizontal.
- GHI needed (measured/forecasted).
- Sunny spells can be problematic.

Diffuse + Nowcasting Algorithm

- Uses forecasted irradiation data.
- Apply the same algorithm for 15 min.
- Consider previous position and forecasted irradiance.



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METHODOLOGY – SOLAR TRACKER ALGORITHMS (2)

ANALYTICAL ALGORITHM

- Previous algorithms switch between Astronomical-horizontal.
- **Optimal angle could be an intermediate position between horizontal and Astronomical.**
- Isotropic sky considered[1].
- GHI needed (measured/forecasted).

$$G_{POA} = G_B + G_D + G_G$$

$$G_B = DNI \cdot cos(AOI)$$

$$G_D = DHI \cdot \frac{1 + cos\,\beta}{2}$$

$$G_G = GHI \cdot a \cdot \frac{1 - cos\,\beta}{2}$$

$$cos(AOI) = cos\,\theta_s \cdot cos\,\beta + sin\,\theta_s \cdot sin\,\beta \cdot cos(\gamma_s - \gamma)$$

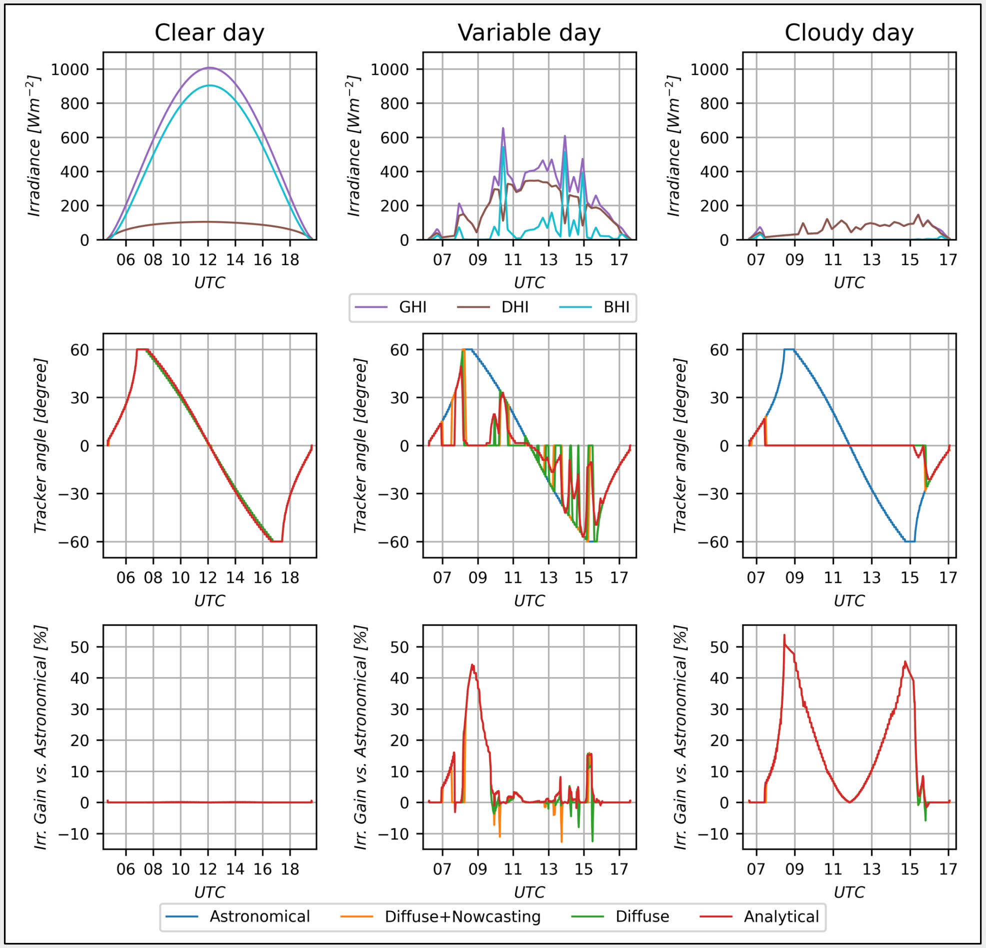
$$\frac{\partial \boldsymbol{G_{POA}}}{\partial \boldsymbol{\beta}} = \frac{\partial G_B}{\partial \beta} + \frac{\partial G_D}{\partial \beta} + \frac{\partial G_G}{\partial \beta} = \mathbf{0}$$

Max. Irradiance condition, as function of β

$$\beta_{opt} = arctan\left(\frac{DNI \cdot sin\,\theta_s \cdot cos(\gamma_s - \gamma)}{\frac{DHI - GHI \cdot a}{2} + DNI \cdot cos\,\theta_s}\right)$$

[1] B. Liu, R. Jordan, *Solar Energy* 1963, 53.

METHODOLOGY – SOLAR TRACKER ALGORITHMS (3)



Differences between algorithms depend on the radiation components

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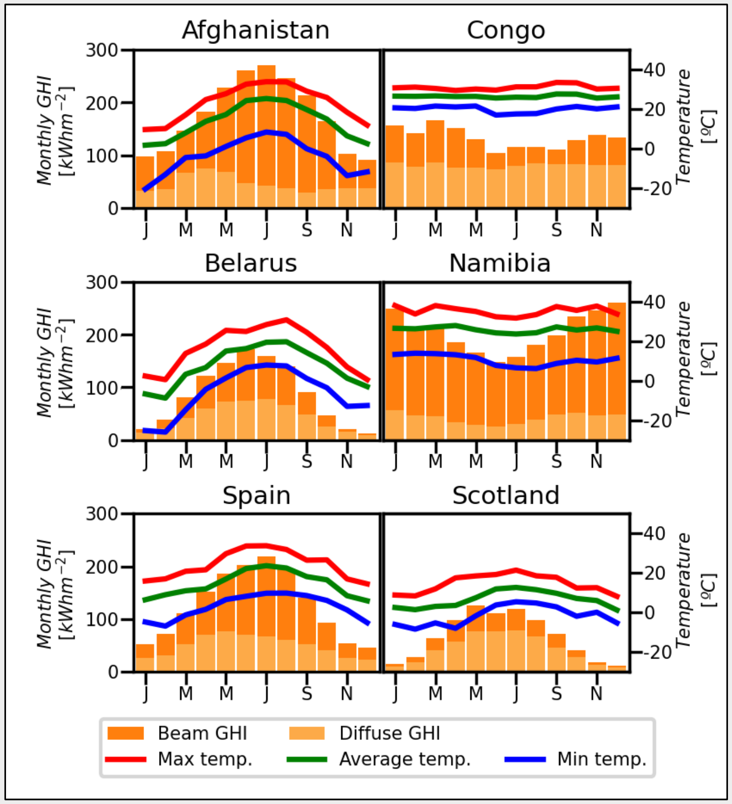
METHODOLOGY – SOLAR RADIATION & METEOROLOGICAL DATA



Location	LAT. [º]	LON. [º]	Reference climate	H_{GHI} [kWh·m^{-2}]	H_{DHI} [kWh·m^{-2}]
Afghanistan	33.77	63.92	High elevation	2113	544
Congo	-3.50	13.01	Tropical humid	1591	974
Belarus	54.00	27.50	Temperate continental	1049	527
Namibia	-20.75	14.02	Subtropical arid	2455	499
Spain	42.80	-1.60	Subtropical coastal	1527	600
Scotland	57.04	-3.61	Temperate coastal	808	528

- Selected sites according to **IEC 61853-4** (reference climates)
- Generation of **one-minute resolution TMY** based on:
  - CAMS & MERRA-2 one-minute resolution data (SoDa platform): 19 years of data (Feb 2004 – Jan 2023)
  - Generation of TMY according to CENER metodology [2] implemented in UNE 206013:2017 standard [3]

[2] C.M. Fernández-Peruchena, et al. *Renewable Sustainable Energy Rev*. 2018, 91, 802.
[3] UNE 206013:2017. *Solar thermal electric plants. Procedure for the generation of solar radiation percentiles years*. UNE:Normalización Española, 2017.

METHODOLOGY – ESTIMATION OF ENERGY PRODUCTION (1)

Evaluation demands a software tool that enables:

- **High resolution** data (1 minute)
- Programming **any solar tracking algorithm**
- Calculating **reliability factors** of solar tracker

SIMPV: PV plant simulation software developed by CENER based on open-source **pvlib python** library; structured in two main modules:

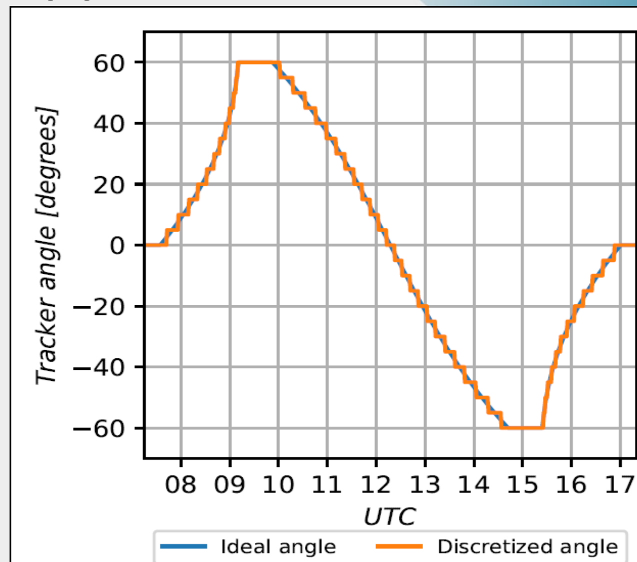
- 1. Estimation of Effective Irradiance on the Plane of Array (POA)
- 2. Estimation of the Electrical Output of the PV installation

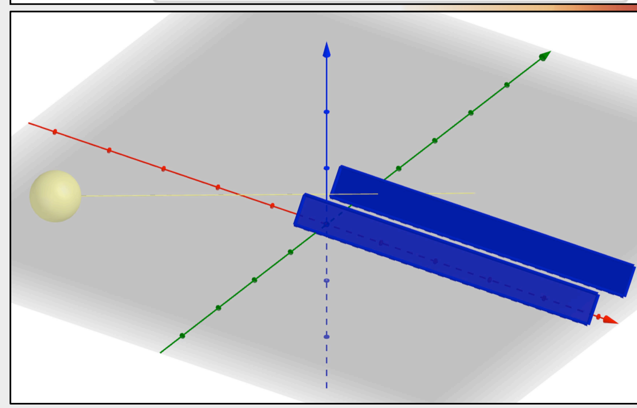
POWERED BY pvlib python

1.Estimation of Effective Irradiance on POA.

Considered effects:

- **Real solar tracker movement** (non-continuous movement) .
- **Anisotropic model** for estimating POA irradiance.
- **2D Inter-row shadings** (self-shading) by trigonometrical relationship between PV modules.
- Irradiance derates (IAM, soiling, horizon...)





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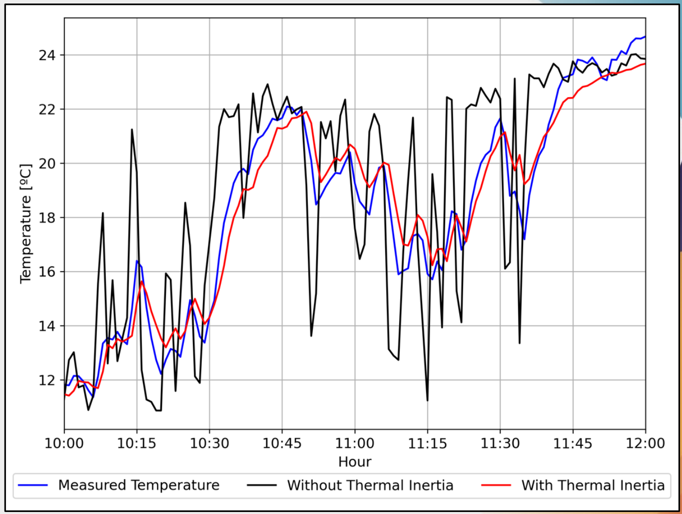
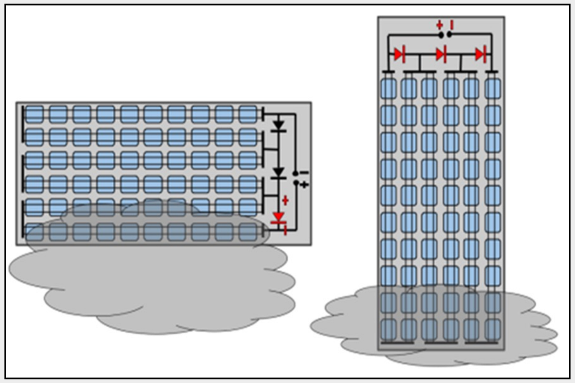
METHODOLOGY – ESTIMATION OF ENERGY PRODUCTION (2)

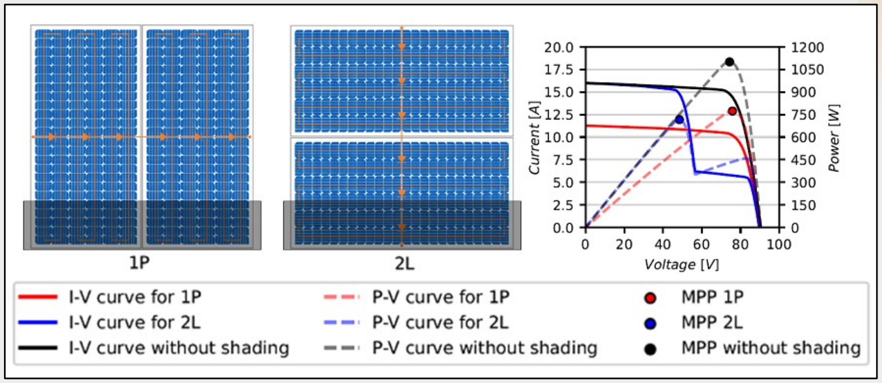
2.Estimation of Electrical Output of PV plant.

Considered effects:

- **Thermal inertia** considered.
- **Full I-V curve** at the DC input of the inverter.
- **Electrical effect of inter-row shadings** (depending on PV module placement, technology and cell type: full cell, half-cell)
- Electrical derates (G-T losses, mismatch losses, ohmic losses…)







METHODOLOGY – STUDY SCENARIOS

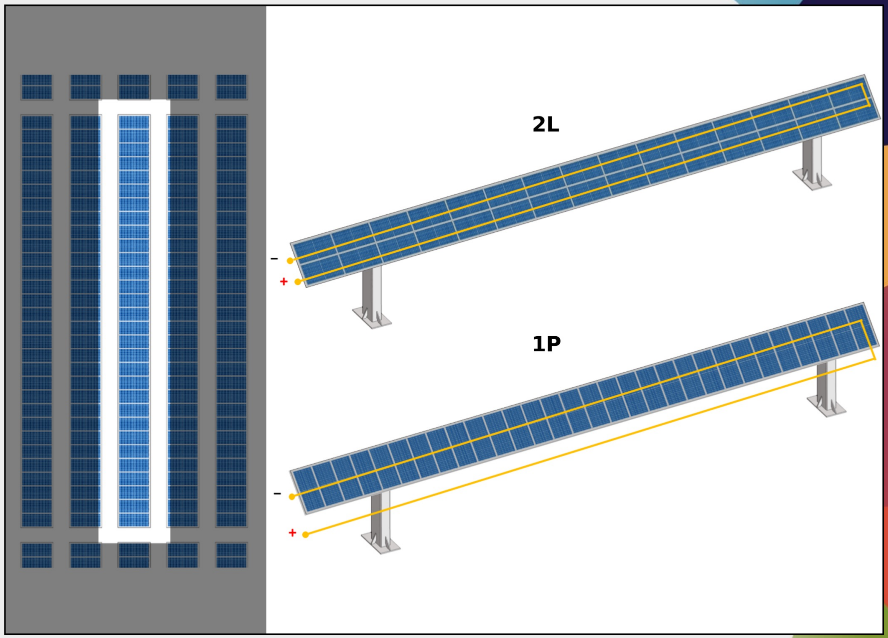
PV installation

- One horizontal single-axis solar tracker in the centre of the plant.
- PV modules: A string (series connected) of 30 monofacial PV modules “half-cell”, 575 Wp, 2.4×1.1 m
- Two module placement
  - **1P** (portrait) Disposition: Row spacing of 6 m
  - **2L** (landscape) Disposition: Row spacing of 5.5 m

  Both dispositions have the **same GCR (0.4)** → DC output **only depends on the electrical connection**.
- Annual albedo of 0.25.

Solar Tracker Mechanical Drive

- Step Movement: 1.5 degrees
- Turning speed: 10 degrees per minute



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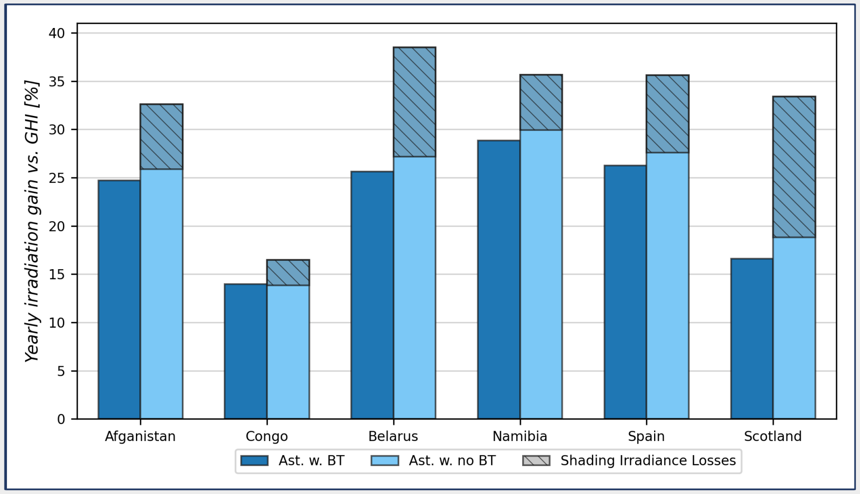
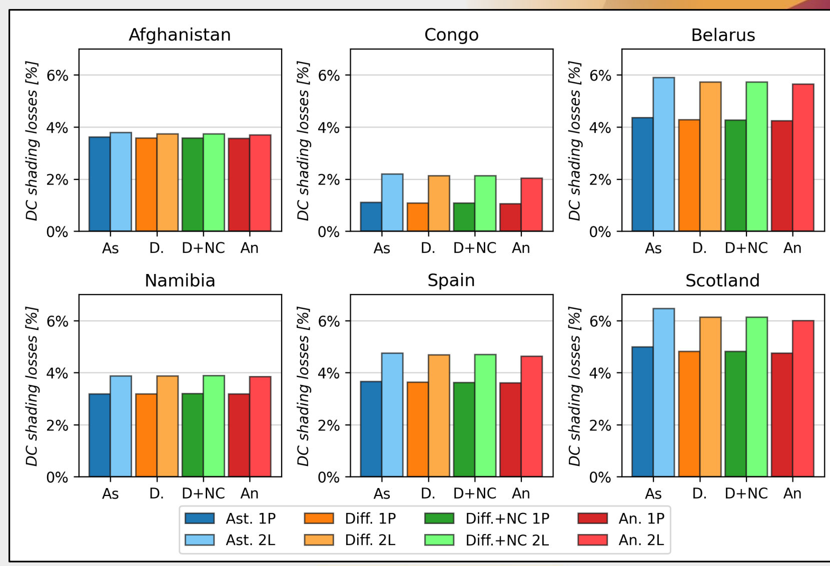
RESULTS – BACKTRACKING STRATEGY (BT)



1. Comparison of all solar tracker algorithms with themselves in all considered sites **with and without BT**

- **Irradiance gain without BT is decreased** due to irradiance beam losses.



- Depending on PV modules disposition, the DC shading losses are:
  - 1P: 1.2 % - 3.3 %
  - 2L: 2.4 % - 5.7 %

- Differences between 1P and 2L shading losses **depends on diffuse fraction and latitude**.

- **DC shading losses are avoided with BT**.

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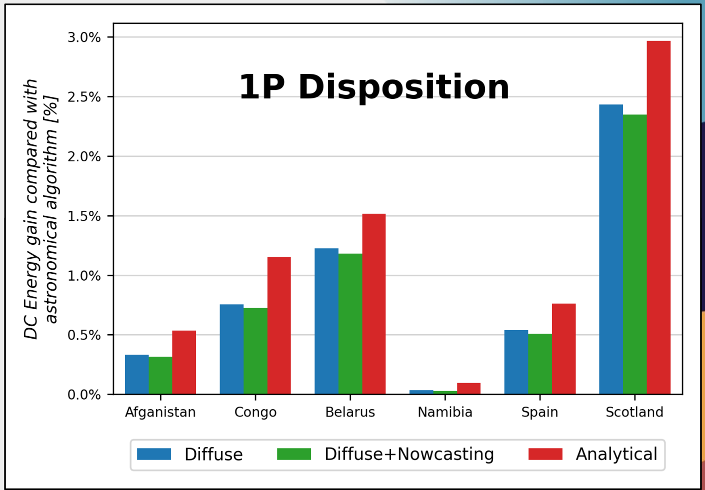
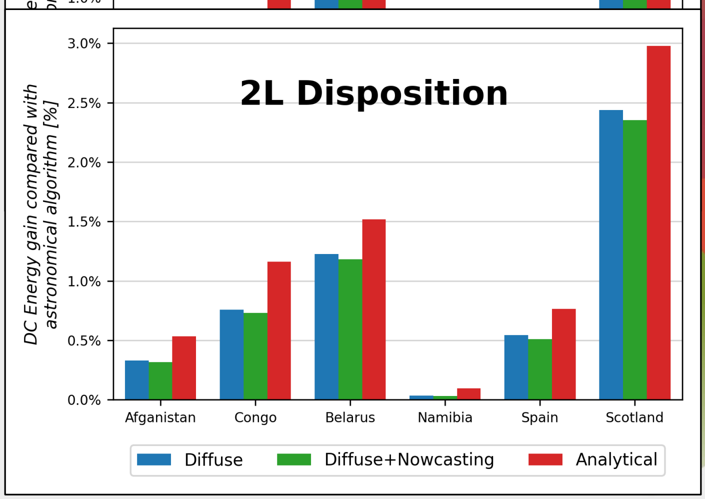
RESULTS – GAIN OF ALGORITHMS vs. ASTRONOMICAL

2. Comparison of detailed solar tracking **algorithms vs. Astronomical Algorithm** in all considered sites (all with BT)

- Studied algorithms **present a DC energy gain** compared with Astronomical.
- **Analytical** outperforms the others
- **The higher diffuse fraction, the higher gain:**
    - **Namibia** (Lowest diffuse fraction): Up to **0.09%**
    - **Scotland** (Highest diffuse fraction): Up to **2.96%**
- **Application of BT causes no dependence** of physical disposition of PV modules (as expected)





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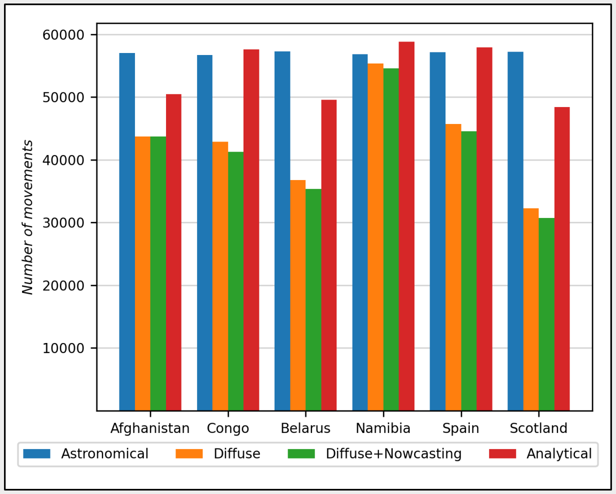
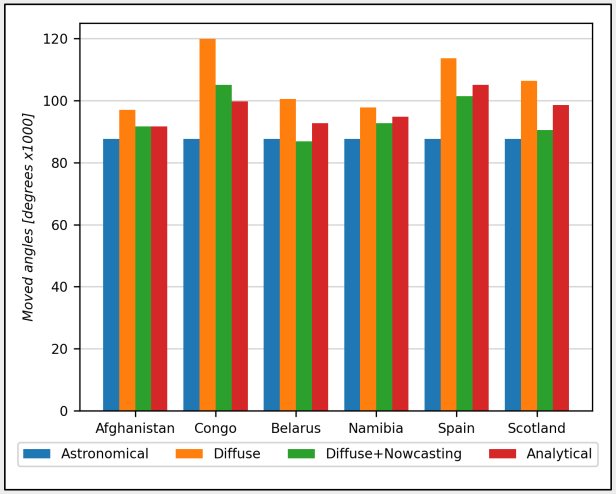
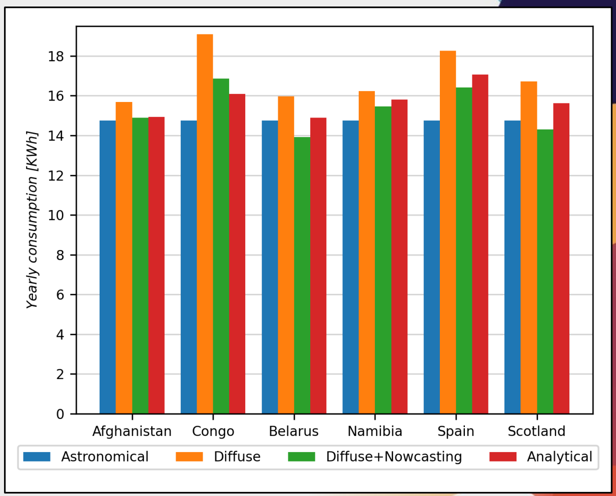
RESULTS – RELIABILITY FACTORS

3. Comparison of all considered solar tracking algorithms in terms of **movements of the solar tracker.**







Highest **number of movements:** Astronomical & Analytical Algorithm

Largest **number of angles moved**: Diffuse

Highest **tracker consumption:** Diffuse

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SUMMARY & CONCLUSIONS

SUMMARY:

- In-depth & **high-resolution study** performed for **four solar single-axis tracking algorithms**.
- Proposed **new algorithm** called Analytical Algorithm.

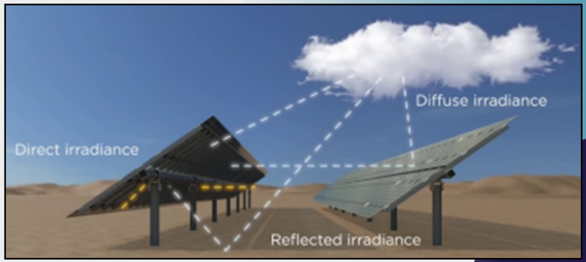
CONCLUSIONS:

- **Backtracking strategies are necessary** on all solar tracking algorithms.
- **Module layout have an impact** on PV production when **inter-row shadings** applies.
- The **performance** of the tracking algorithms depends on the **climatological conditions**.
- Analyzed algorithms **outperform the Astronomical** in all studied locations.
- **Analytical** Algorithm could reach **up to 3% energy** gain compared to the Astronomical.

Current horizontal single axis solar tracker presents a chance for designing and implementing new tracking algorithms in an easy way, which could increase the performance of the PV plant without adding new expensive elements or technologies

ONGOING & FUTURE WORKS

- Evolution of Analytical algorithm considering **anisotropic models** for the optimal tilt calculation.
- Modelling of **bifacial** PV simulation with **in-house CENER ray-tracing** software (Tonatiuh) considering non-uniformity of back side.
- Development of **new solar tracker algorithms** for specific systems (e.g. agriPV, bifacial analytical…)
- **Prototype of control system** to apply all the solar tracking algorithms in a real solar tracker (CENER experimental PV installation)



Tonatiuh™
ray tracing for solar energy

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Thank you for your attention!

CENER

Solar Energy Technologies
& Storage Department

golivares@cener.com

Ciudad de la Innovación, 7
31621 Sarriguren, Spain

+34 948 252 800

www.cener.com

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