

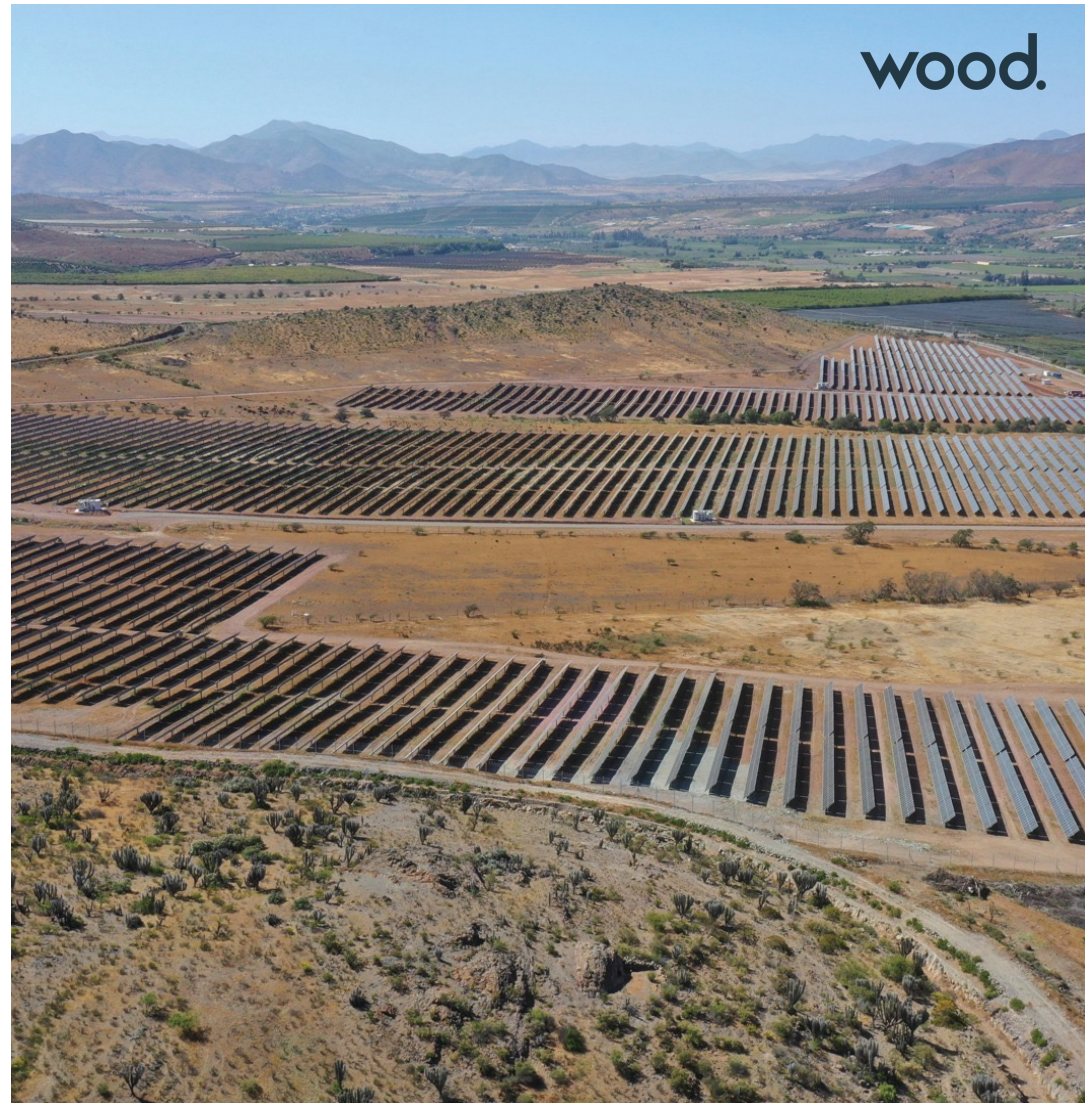
Validation of Terrain Losses & Energy Yield Optimization

Case Study

Kerstin Lukrafka

Renewable Energy Consultants

12 May 2025



Energy Yield Assessments – Key for Business Decisions



- Financing
- Investment Decisions
- Claims
- Operation Assessment

Example News

DNV

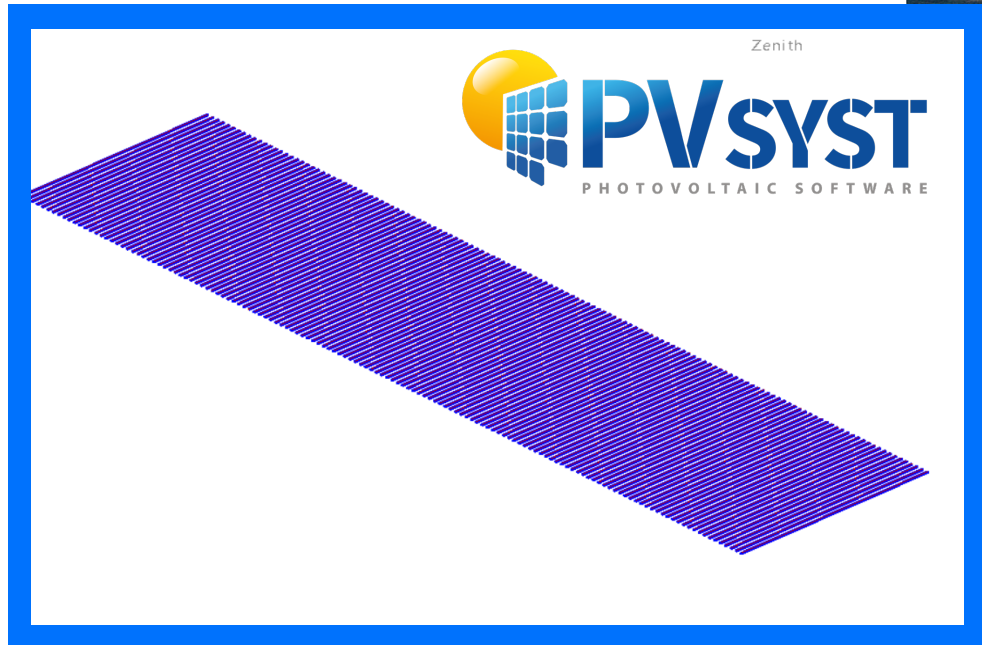
Uneven terrain driving up to 6% of performance losses

KWH ANALYTICS

1-in-3 solar assets under development are overstating P50 estimates by >5%

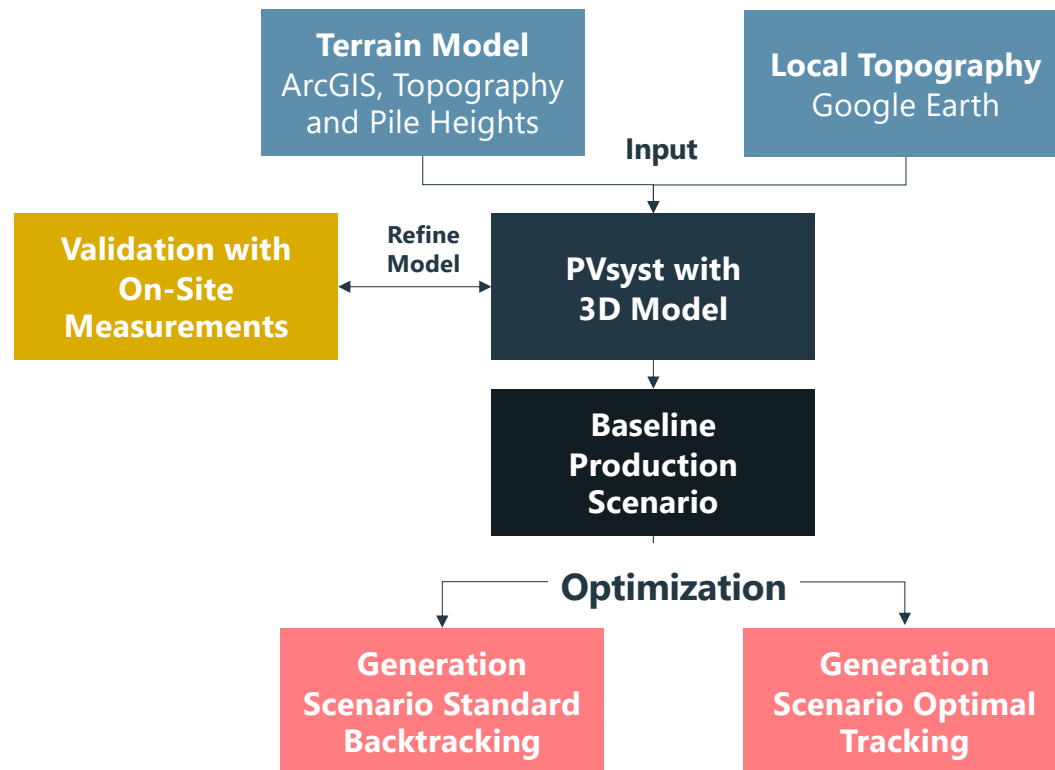
wood.

Common Modelling Practice





Modelling Approach



Considerations:

Selected PV Module Technology

As-built/IFC Design

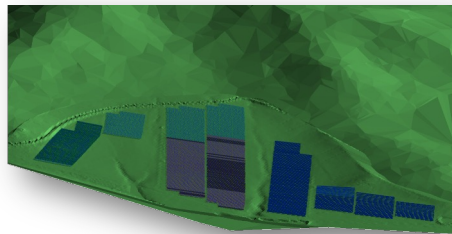
Local Shading

Varying Slope

Seasonality

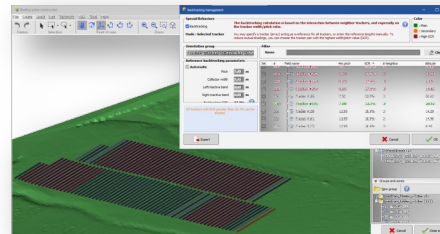
wood.

Generation Scenario – Standard Backtracking (Tuned GCR)



3D Shading Scene

- Import As-Built Design + Topography
- Definition of orientations by Tracking Control Area



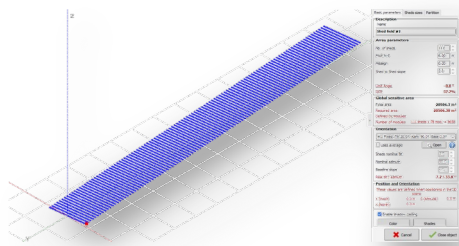
Backtracking Management

- Definition of Lead Tracker (No Shading Enabled)
- Pitch manipulation



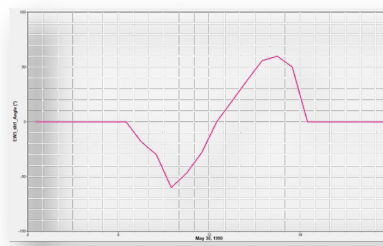
Year	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	P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Generation Scenario – Optimal Tracking (Row-by-Row)



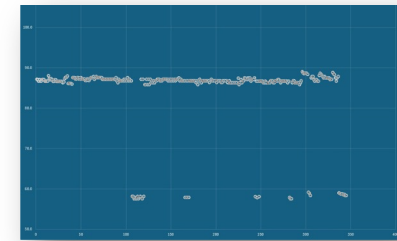
Fixed Tilted System

- Identification of on-site conditions for each tracker (E-W slope, tilt)
- Simulation of Fixed Tilted System with varying slope



Hourly Tracking Angle

- Identification of optimal tracking angles for trackers in hourly steps



Production Calculations

- Calculation of production for each tracker
- Calculation of inverter output



Production Output

Optimization of irradiance capture and losses

Case Study



Project Information:

- Location: Ovalle, Chile
- DC Capacity: 12,505 kWp
- Export Limit: 9,000 kW
- Central Inverter: 3 (3,125 kW)
- Tracker Control Areas: 3
- Modules: 480Wp, half-cut cell, bifacial
- **E-W Slope:** **1° to 12°**
- **Axis Tilt:** **-4° to +8°**

Available information:

- Site high-resolution topography
- As-built pile heights and locations
- As-built design
- Operational data 2024

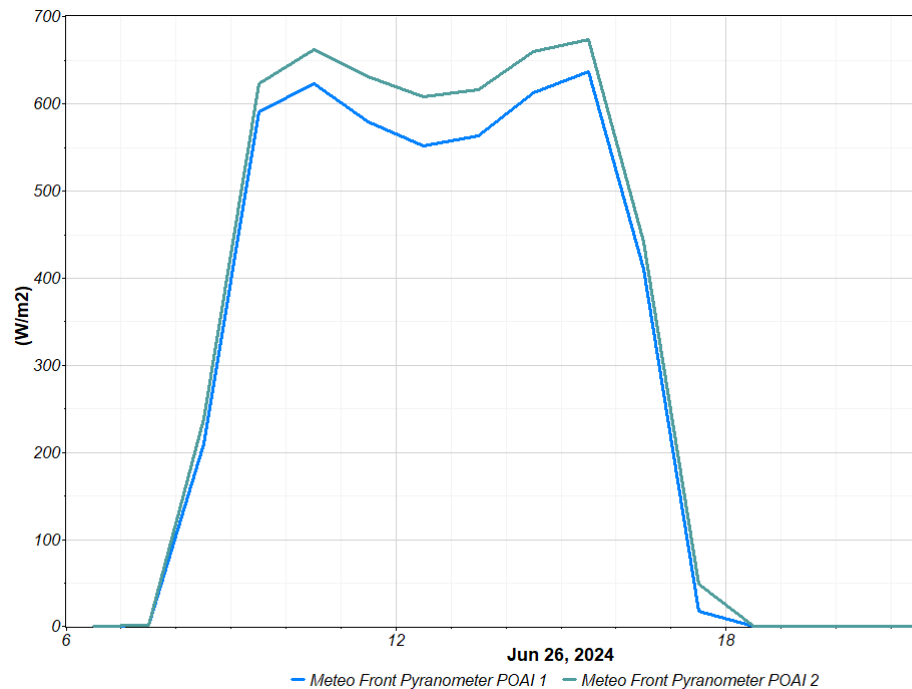
wood.

Key Findings from the Validation Process



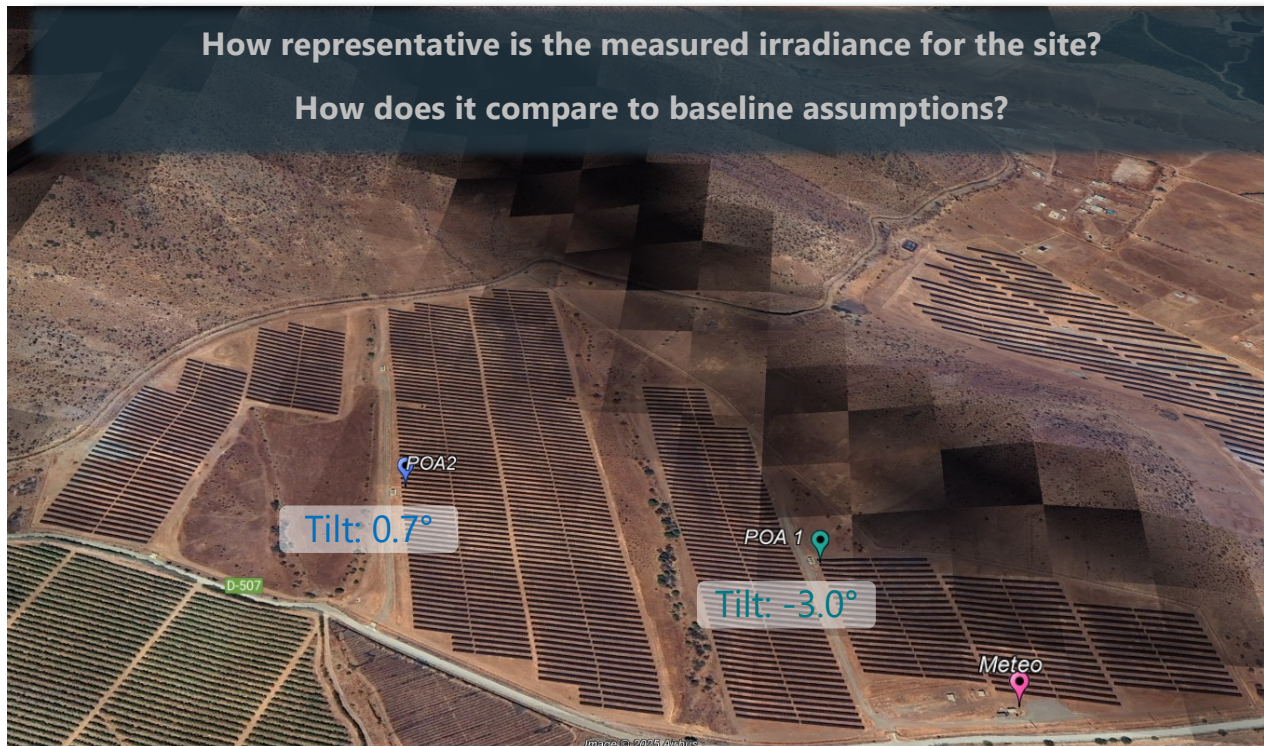


On-Site Measurements



- POAI 2 versus POAI1 2024: **+3.8%**
(70% data availability)
- POAI Sim (GHI Meas vs GHI Sat Hist) 2024: -5.2%
(Jan-Aug data availability)
- POAI1 versus Simulated Flat Sat Hist 2024: -6.7%
(40% data availability)
- POAI2 versus Simulated Flat Sat Hist 2024: -2.7%
(40% data availability)

Why Sensor Location is Essential



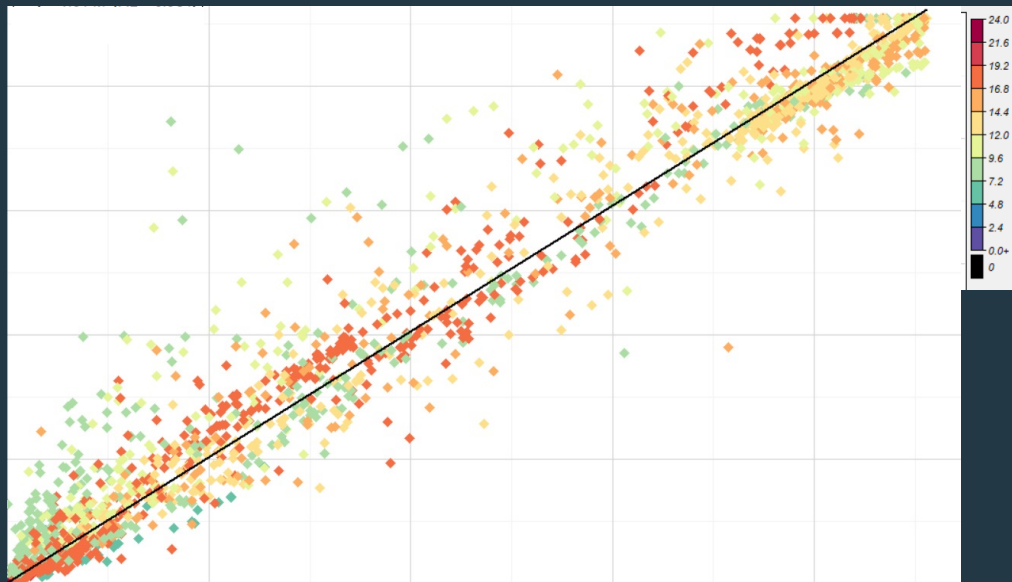
Key Factors affecting Solar Resource Measurements:

1. Tracker Axis Tilt
2. Location (Local Shading)
3. Tracking Configuration

How does this impact:

- Performance Guarantees
- Operation Monitoring
- Site Adaptation of Satellite Data

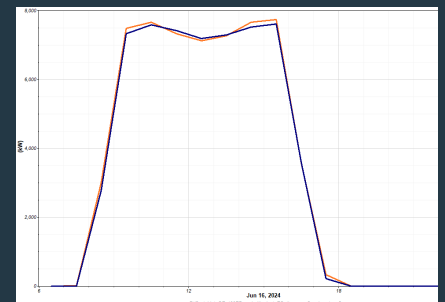
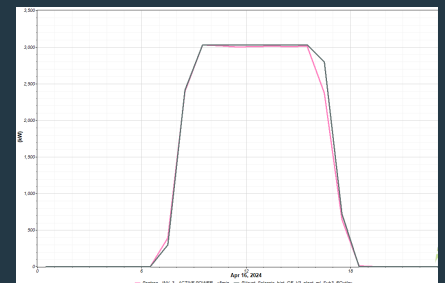
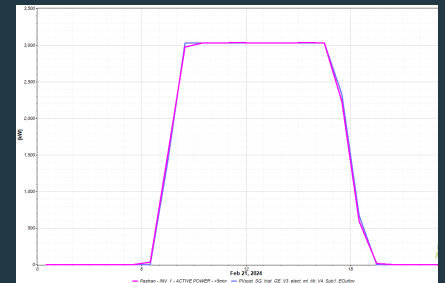
Case Study - Validation



Comparison of Simulated Inverter Output with Measured Inverter Output

- Least-squares fit slope: 1.014
- R-squared: 0.984

Clear-sky day Images:



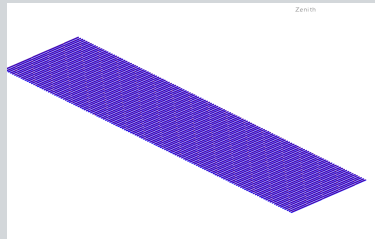
Simulation Results



Simulation Results - Case Study

Baseline Scenarios

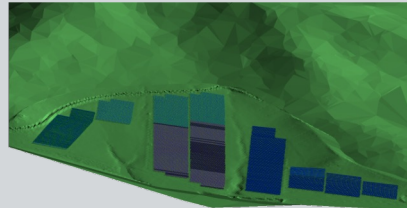
Flat Terrain



Inverter Output P50 TMY:

27,933 MWh/year

As-Built Layout



Inverter Output P50 TMY:

27,238 MWh/year



-2.5%

estimated production

Optimization Scenarios

Tuned Backtracking (1 GCR Setting)

+265MWh

+1.0% estimated production vs as-built

+1,271
MWh

Tuned Backtracking (2 GCR Settings)

+4.7% estimated production vs as-built

+1,808
MWh

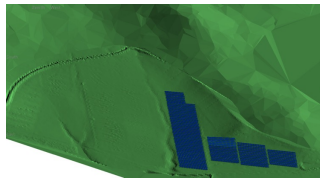
Optimal Row-by-Row Tracking

+6.6% estimated production vs as-built

wood.

Simulation Results - Case Study

Area 1



Specifications

South and north tilted trackers
Largest slope variation

E-W Slope	Axis Tilt
Ave: 4.4°	Ave: 0.0°
Min: 1.3°	Min: -3.5°
Max: 11.6°	Max: 1.5°

Tuned Standard Backtracking

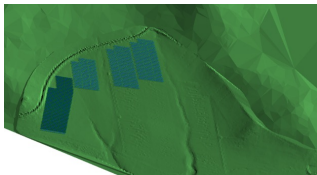
Implemented: 6.0m pitch
Optimized 1 setting: **7.0m pitch**
Optimized 2 settings:

- **Morning 7.0m pitch**
- **Afternoon: 4.5m pitch**

Simulation Results

-3.6% flat vs as-built
+0.7% GCR tuning (1 setting) vs as-built
+5.8% GCR tuning (2 settings) vs as-built
+8.3% Optimal Row-by-row tracking vs as-built

Area 2



Specifications

Largest tilt variation
Some slope variation

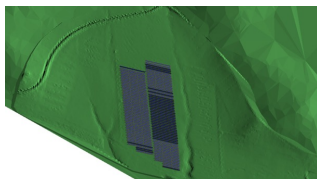
E-W Slope	Axis Tilt
Ave: 3.6°	Ave: 3.4°
Min: 0.8°	Min: 1.3°
Max: 6.2°	Max: 7.5°

Implemented: 6.0m pitch
Optimized 1 setting: **7.0m pitch**
Optimized 2 settings:

- **Morning 7.0m pitch**
- **Afternoon: 4.5m pitch**

-1.8% flat vs as-built
+0.8% GCR tuning (1 setting) vs as-built
+5.7% GCR tuning (2 settings) vs as-built
+6.1% Optimal Row-by-row tracking vs as-built

Area 3



Specifications

Lower tilt and slope variations

E-W Slope	Axis Tilt
Ave: 2.9°	Ave: 1.3°
Min: 0.8°	Min: 0.4°
Max: 4.7°	Max: 2.2°

Implemented: 6.0m pitch
Optimized 1 setting: **5.0m pitch**
Optimized 2 settings:

- **Morning 6.5m pitch**
- **Afternoon: 5.0m pitch**

+0.2% flat vs as-built
+1.4% GCR tuning (1 setting) vs as-built
+2.5% GCR tuning (2 settings) vs as-built
+5.6% Optimal Row-by-row tracking vs as-built

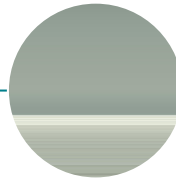
wood.

Future Work



Collaboration

Collaboration with tracker manufacturers and plant owners to better understand tracking algorithms and settings.



Uncertainty Analysis

Analysis and estimation of uncertainties from modelling limitations and simplifications.



Validation

Validation of optimization scenario results with operational data.

wood.

Modelling Limitations

Baseline Production Scenario:

- Linear best-fit approach for tracker tilts
- Average tilt of each orientation is used for irradiance calculation
- No tilt manipulation possible for the backtracking strategy to reflect actual tracking setting
- Hourly simulations

Standard Backtracking Tuning Production Scenario:

- One front tracker row of each orientation is considered to not cast shadows

Optimal Tracking Production Scenario:

- No string mismatch included (individual tracker MPPT)
- No consideration of local horizon, inhomogeneous pitch and inhomogeneous tracking angles

