Development of a Simulation Model for Optimizing Orientation, Tilt and Row Spacing in Ground-Mounted Solar Photovoltaic Parks

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hybr2d Theory of Hybrid Systems Informatik 2 | RWTH AACHEN UNIVERSITY

Motivation

- Photovoltaic as a key technology in Germany's energy transition

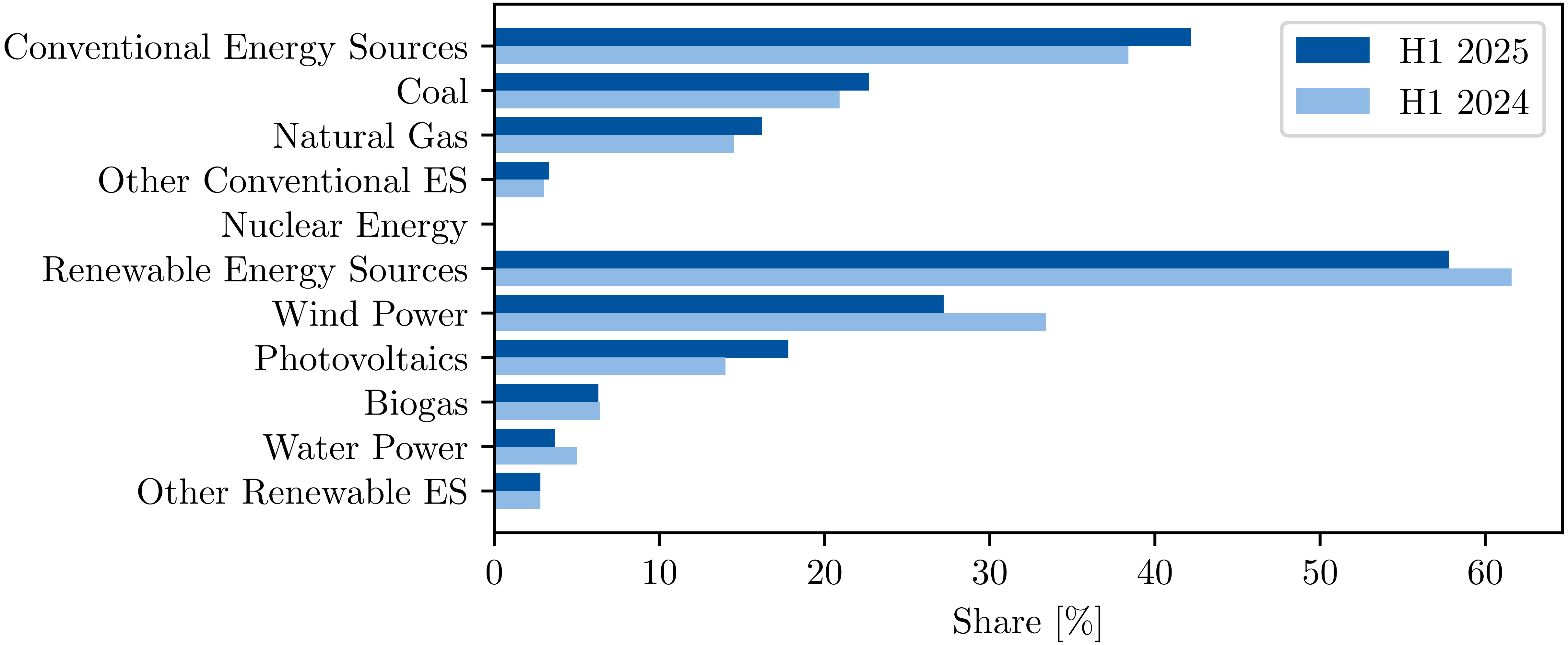


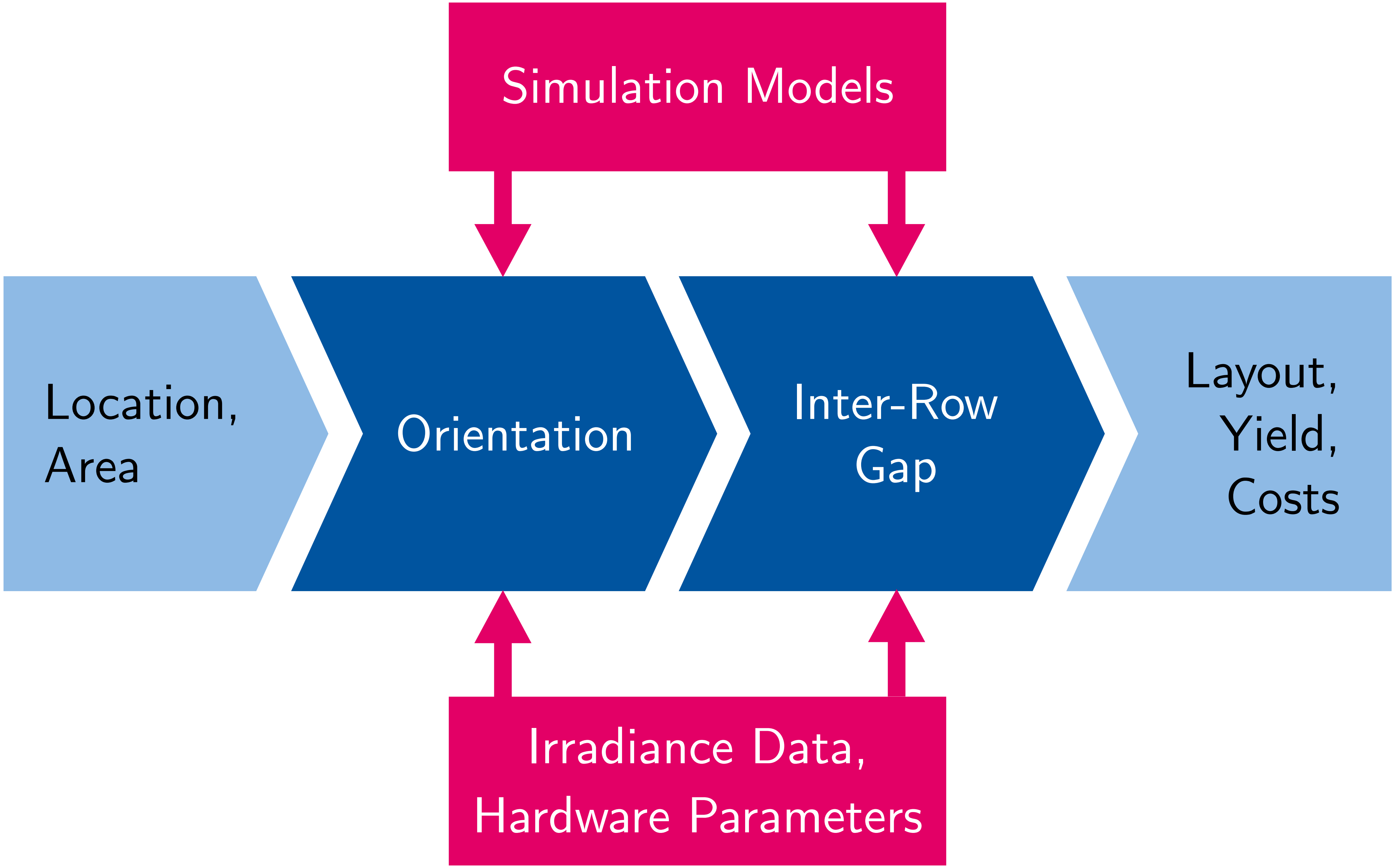
Figure: Electricity feed-in from renewable and conventional energy sources in Germany

Motivation

- Efficiency of PV parks sensitive to
  - PV module orientation: azimuth and tilt angles
  - PV module row spacing

→ Optimization framework determining ideal layout parameters

Optimization Framework



Agenda

Optimal Module Orientation

Optimal Module Orientation

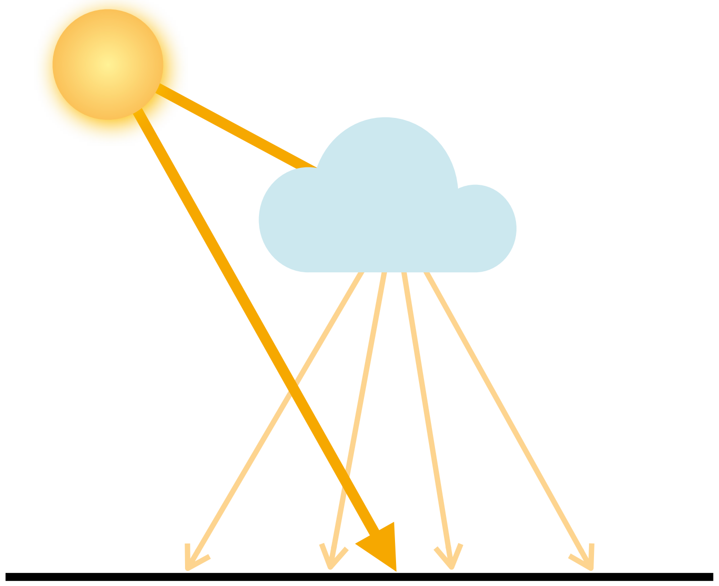
- What is optimal?
  $\rightarrow$ Capture the most irradiance during the whole year

- How to simulate annual plane-of-array (POA) irradiance?
  - Depends on weather conditions $\rightarrow$ needs irradiance data

Irradiance Data

Optimal Module Orientation

- Irradiance Components
  - Direct normal irradiance (DNI)
  - Diffuse horizontal irradiance (DHI)
  - Global horizontal irradiance (GHI)
- Can be simulated → Ineichen Clear-Sky model
  or sourced from databases → PVGIS-ERA5



Optimal Module Orientation

- What is optimal?
  $\rightarrow$ Capture the most irradiance during the whole year
- How to simulate annual plane-of-array (POA) irradiance?
  - Depends on weather conditions $\rightarrow$ needs irradiance data
    $\rightarrow$ Hourly irradiance data with components GHI, DNI and DHI
  - Calculate POA irradiance $\rightarrow$ transposition model

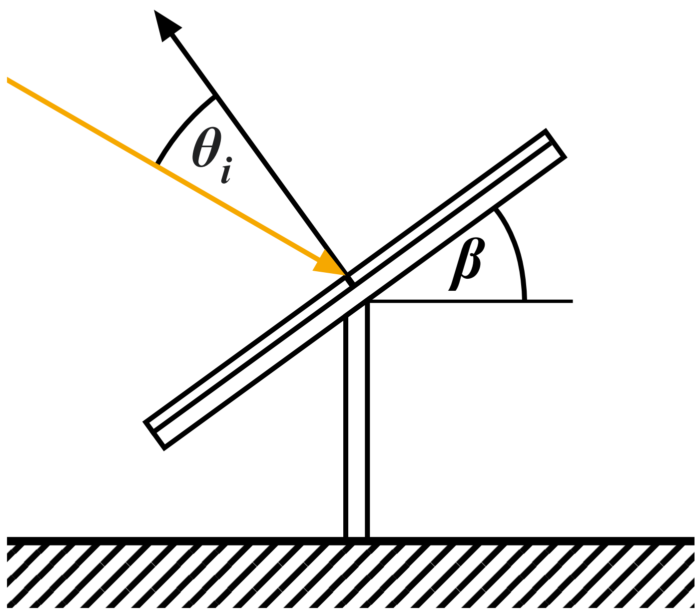
Transposition Model

Optimal Module Orientation

- Isotropic Model
  $\rightarrow$ diffuse radiation uniform across sky dome

$$\mathrm{POA} = \mathrm{DNI} \cdot \cos(\theta_\mathrm{i}) + \mathrm{DHI} \cdot F_\mathrm{sky} + \mathrm{GHI} \cdot \rho \cdot F_\mathrm{ground}$$

$$F_\mathrm{sky} = \frac{1 + \cos\beta}{2} \qquad F_\mathrm{ground} = \frac{1 - \cos\beta}{2}$$



- Perez Model
  $\rightarrow$ anisotropic model

$$\mathrm{POA} = \mathrm{DNI} \cdot \cos(\theta_\mathrm{i}) + \mathrm{DHI} \cdot \left[(1 - F_1) \cdot F_\mathrm{sky} + F_1 \cdot \frac{a}{b} + F_2 \cdot \sin\beta\right] + \mathrm{GHI} \cdot \rho \cdot F_\mathrm{ground}$$

$$a = \max\left(0, \cos\theta_\mathrm{i}\right) \qquad b = \max\left(\cos 85^\circ, \cos\theta_\mathrm{z}\right)$$

Optimal Module Orientation

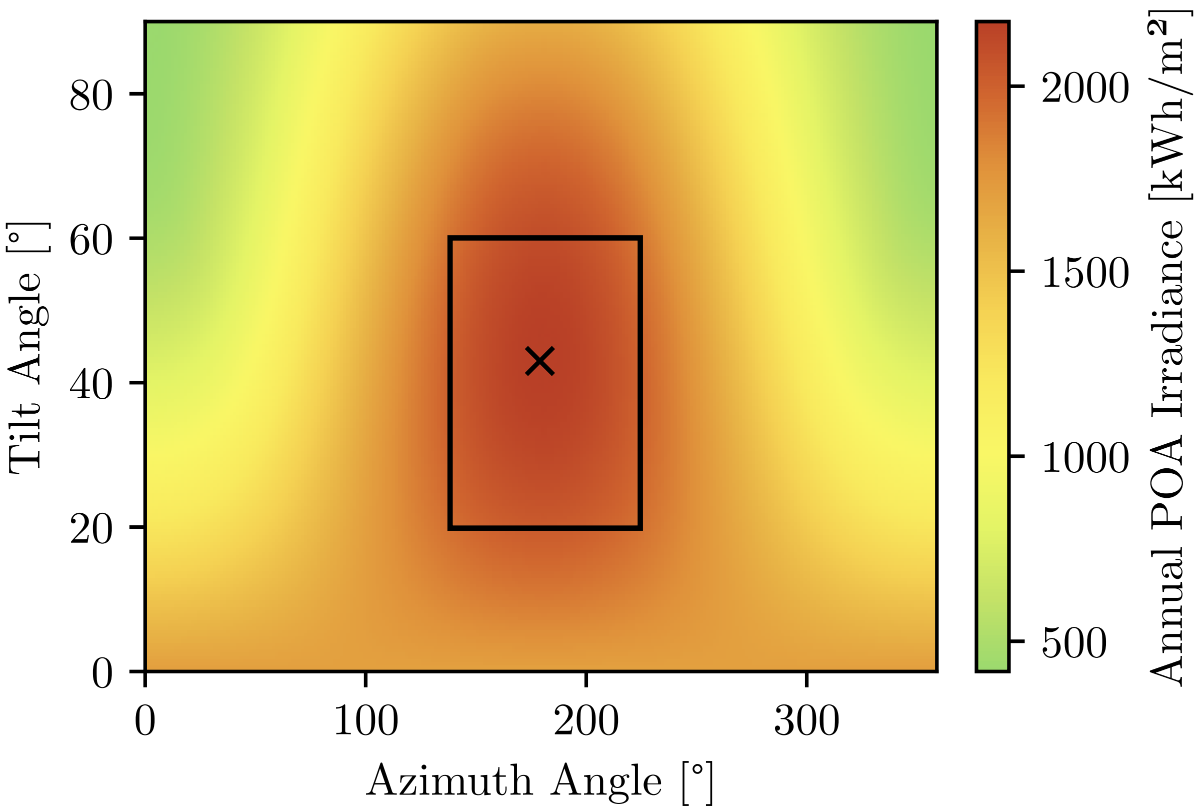
- What is optimal?
  → Capture the most irradiance during the whole year

- How to simulate annual plane-of-array (POA) irradiance?
  - Depends on weather conditions → needs irradiance data
    → Hourly irradiance data with components GHI, DNI and DHI
  - Calculate POA irradiance → transposition model
    → Isotropic and Perez model

  → Transpose each irradiance data point, sum up the transposed data points and norm them to one year

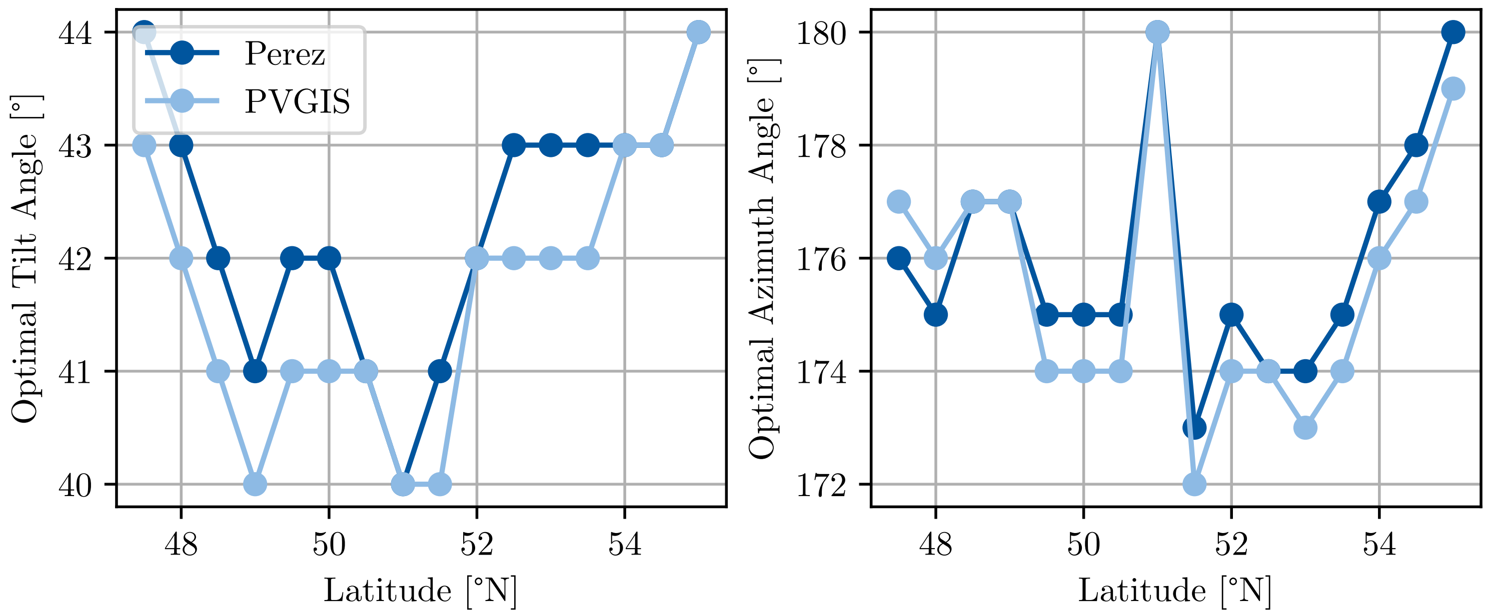
Optimal Module Orientation

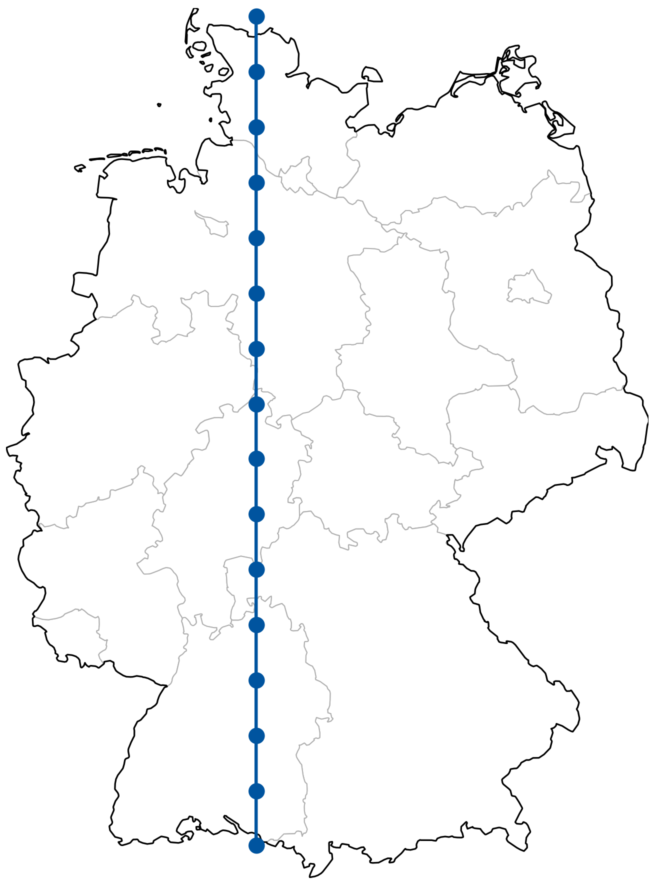
- Optimization algorithm
  - Unbounded grid search
    → try each combination and return the maximum
  - Bounded grid search
    → grid search on reduced search space



Optimal Module Orientation

- Validate simulation results with PVGIS' optimal angles
- Perez model with PVGIS irradiance data





- MAE: 0.625° tilt and 0.75° azimuth

Optimal Module Orientation

- Differences between used models and algorithms

Transposition Model	Isotropic Sky Model	Isotropic Sky Model	Perez Model
Irradiance Data	Clear Sky Model	PVGIS-ERA5	PVGIS-ERA5
Accuracy (MAE)	3.375° tilt 4.9375° azimuth	4.9375° tilt 1.4375° azimuth	0.625° tilt 0.75° azimuth
Unbounded Grid	37.585 s	219.123 s	928.982 s
Bounded Grid	8.458 s	29.065 s	100.283 s
Performance Gain	444.372 %	753.906 %	926.360 %

→ Prefer Perez transposition model over isotropic model

→ Prefer PVGIS irradiance data over clear sky model

→ Prefer bounded grid search over unbounded grid search

Optimal Inter-Row Gap

Optimal Inter-Row Gap

- What is optimal?
  → Trade-off between more module rows and less self-shading

Half-cut Model

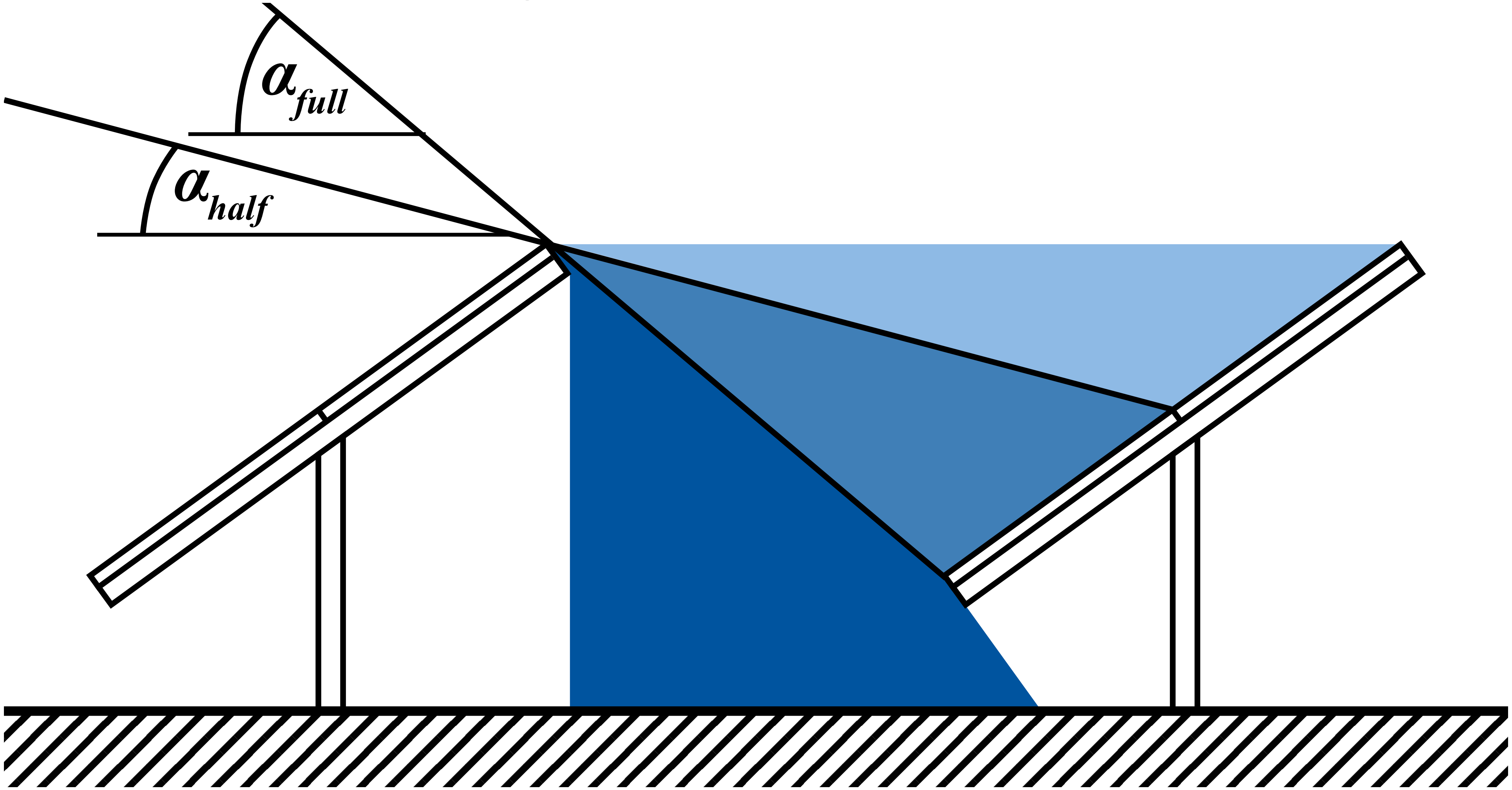
Optimal Inter-Row Gap

- Typically PV modules are split in half horizontally
- If parts of a string are shaded, electricity production drops
- Half-cut modules have one string per half
- Half-cut model $\rightarrow$ apply 50% loss per shaded half

Self-Shading Model

Optimal Inter-Row Gap

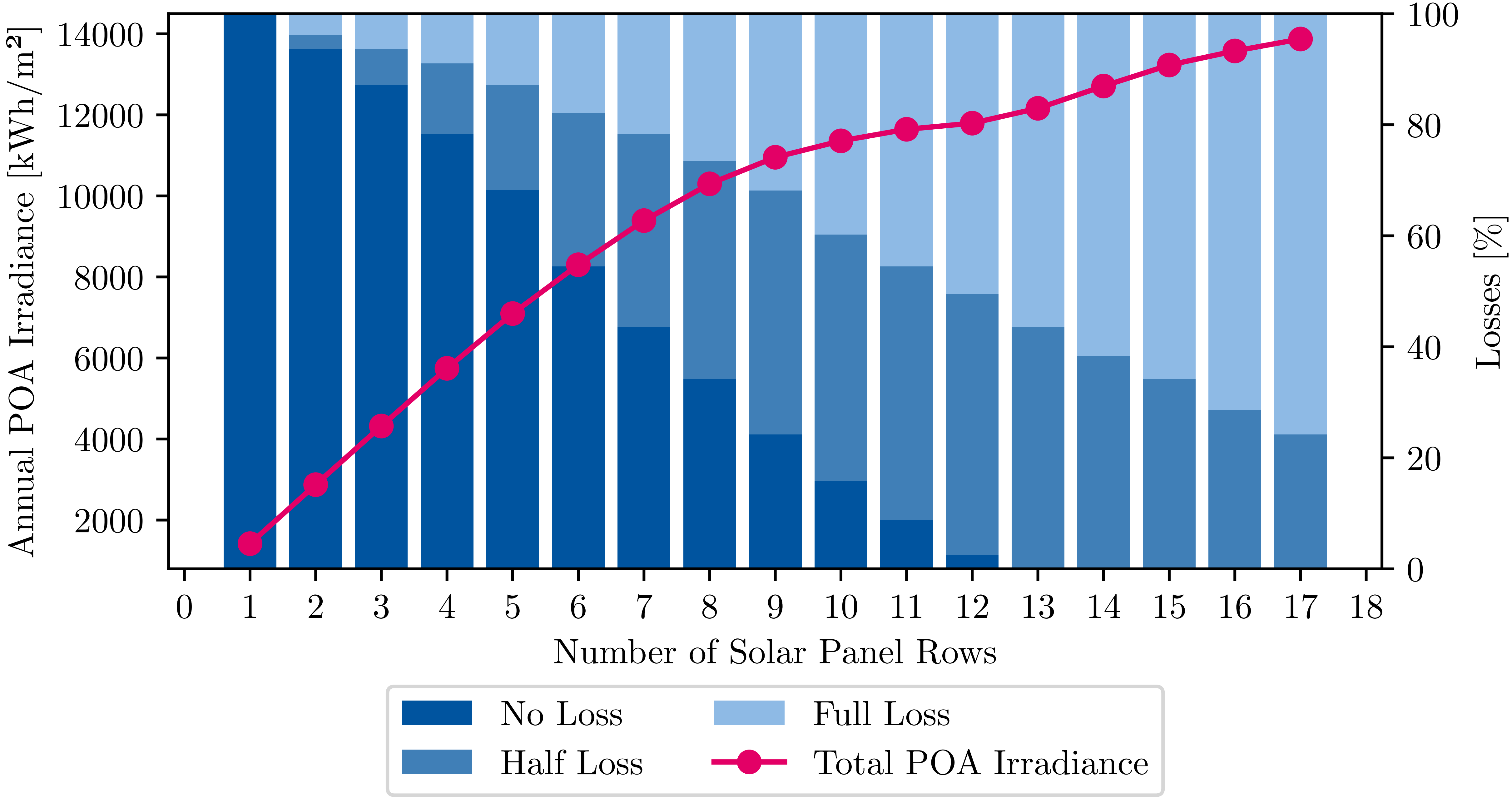
- dark blue: no shading loss
- mid blue: 50% shading loss
- light blue: 100% shading loss



Optimal Inter-Row Gap

- What is optimal?
  $\rightarrow$ Trade-off between more module rows and less self-shading
- Maximize annual POA irradiance
  $\rightarrow$ Apply shading losses to irradiance data

Optimal Inter-Row Gap

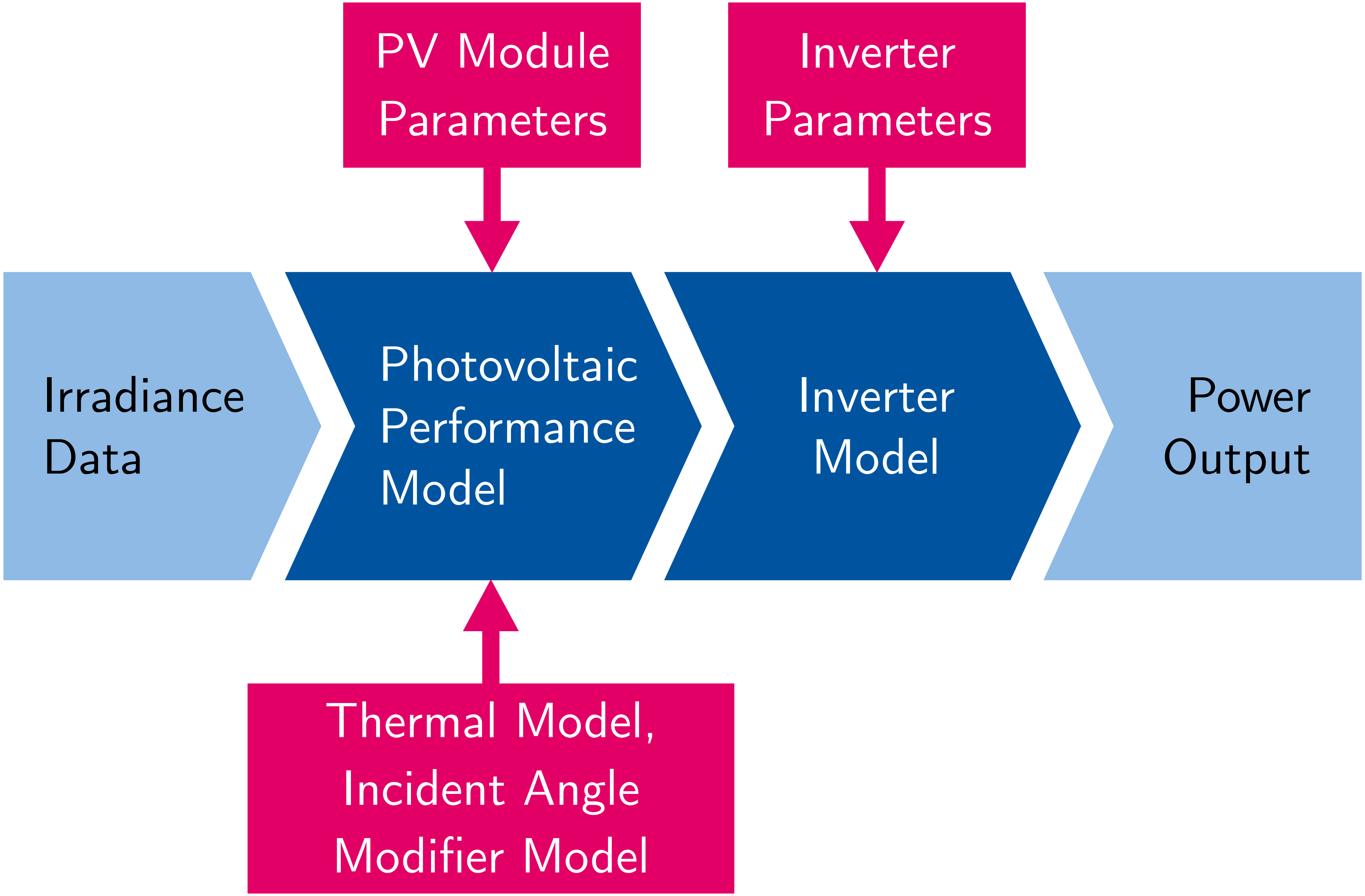


Optimal Inter-Row Gap

- What is optimal?
  → Trade-off between more module rows and less self-shading
- Maximize annual POA irradiance
  → Apply shading losses to irradiance data
  → Smallest gap produces highest annual POA irradiance
- Minimize Levelized Cost of Electricity (LCOE)
  → Account for costs of additional module rows

Simulate Power Output

Optimal Inter-Row Gap



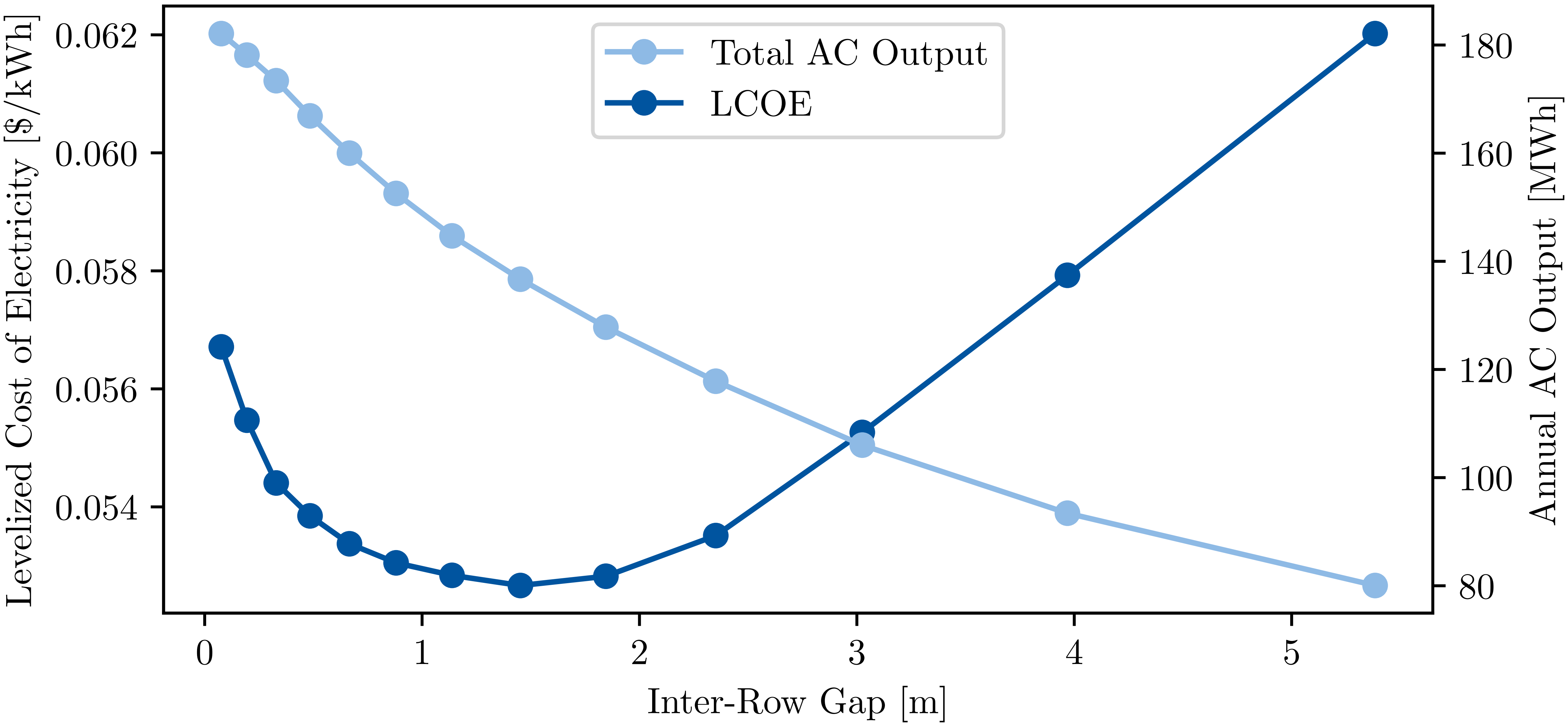
Cost Model

Optimal Inter-Row Gap

Category	**Cost**
Utility Module Cost	372 $\$/\mathrm{kWh_{dc}}$
Utility Inverter Cost	65 $\$/\mathrm{kWh_{ac}}$
Utility Structural Balance of System (SBOS) Cost	30 $\$/\mathrm{m}^2$
Utility Electrical Balance of System (EBOS) Cost	236 $\$/\mathrm{kWh_{ac}}$
Utility Fieldwork Cost	61 $\$/\mathrm{m}^2$
Utility Officework Cost	66 $\$/\mathrm{kWh_{dc}}$
Utility Other Cost	247 $\$/\mathrm{kWh_{dc}}$
Annual Utility Operations and Maintenance (O&M) Cost	16.58 $\$/\mathrm{a}/\mathrm{kWh_{dc}}$

- Derive total expenditures from PV park parameters
- Calculate LCOE $$\mathrm{LCOE} = \frac{\mathrm{cost_{TOTEX}}}{\mathrm{LT} \cdot P_{\mathrm{ac}}}$$

Optimal Inter-Row Gap



Optimal Inter-Row Gap

- What is optimal?
  $\rightarrow$ Trade-off between more module rows and less self-shading
- Maximize annual POA irradiance
  $\rightarrow$ Apply shading losses to irradiance data
  $\rightarrow$ Smallest gap produces highest annual POA irradiance
- Minimize Levelized Cost of Electricity (LCOE)
  $\rightarrow$ Account for costs of additional module rows
  $\rightarrow$ Lowest LCOE is not at smallest gap

Case Study: Solarpark Langenenslingen-Wilflingen

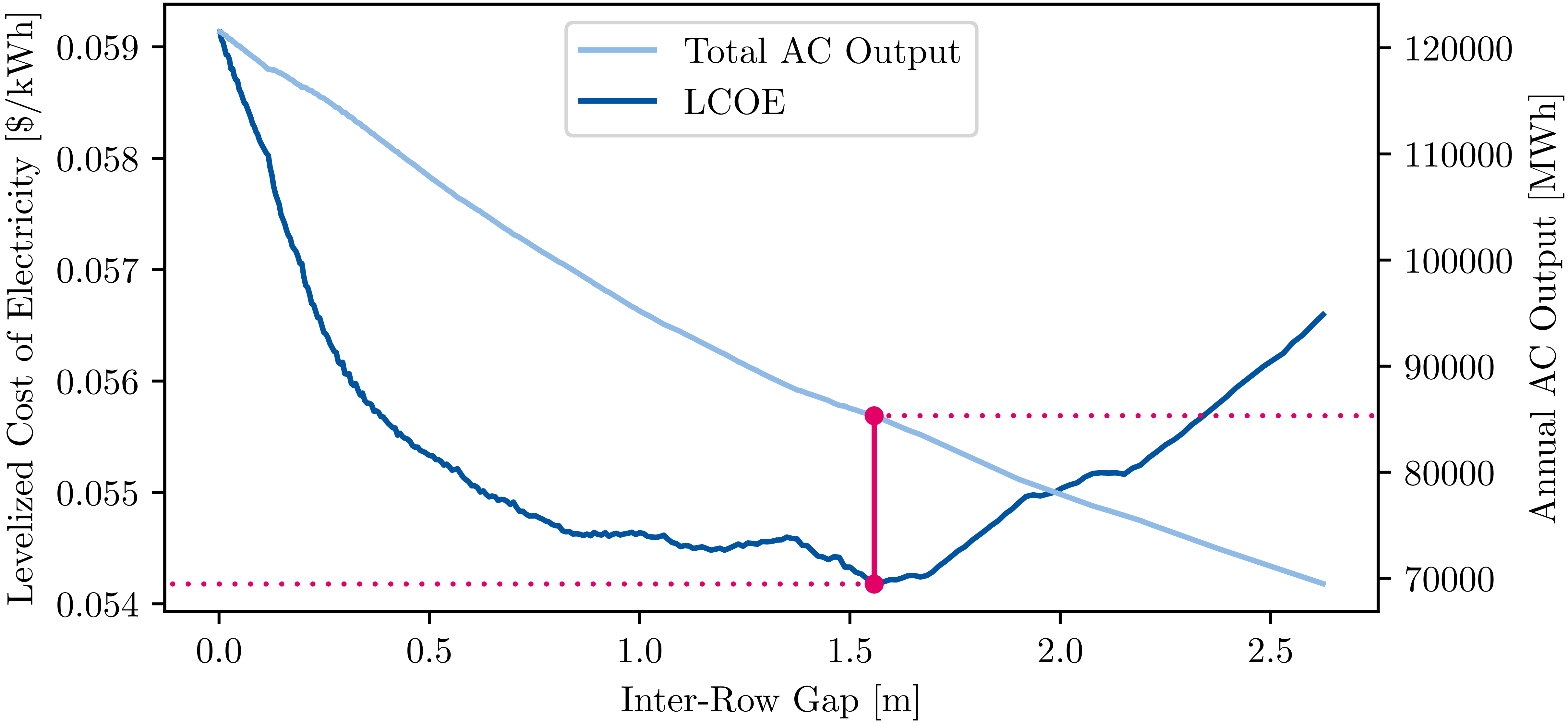
Optimal Inter-Row Gap

- Commenced operation in 2025
- Located in Baden Wuerttemberg, Germany
- 60 ha available area
- extrapolated annual energy production of 89.9 GWh

→ Simulate this park and compare power output at the optimal inter-row gap

Case Study: Solarpark Langenenslingen-Wilflingen

Optimal Inter-Row Gap



→ Optimal inter-row gap of 1.555 m

→ Annual power output of 85.380 GWh at a LCOE of 0.054 $/kWh

Conclusion

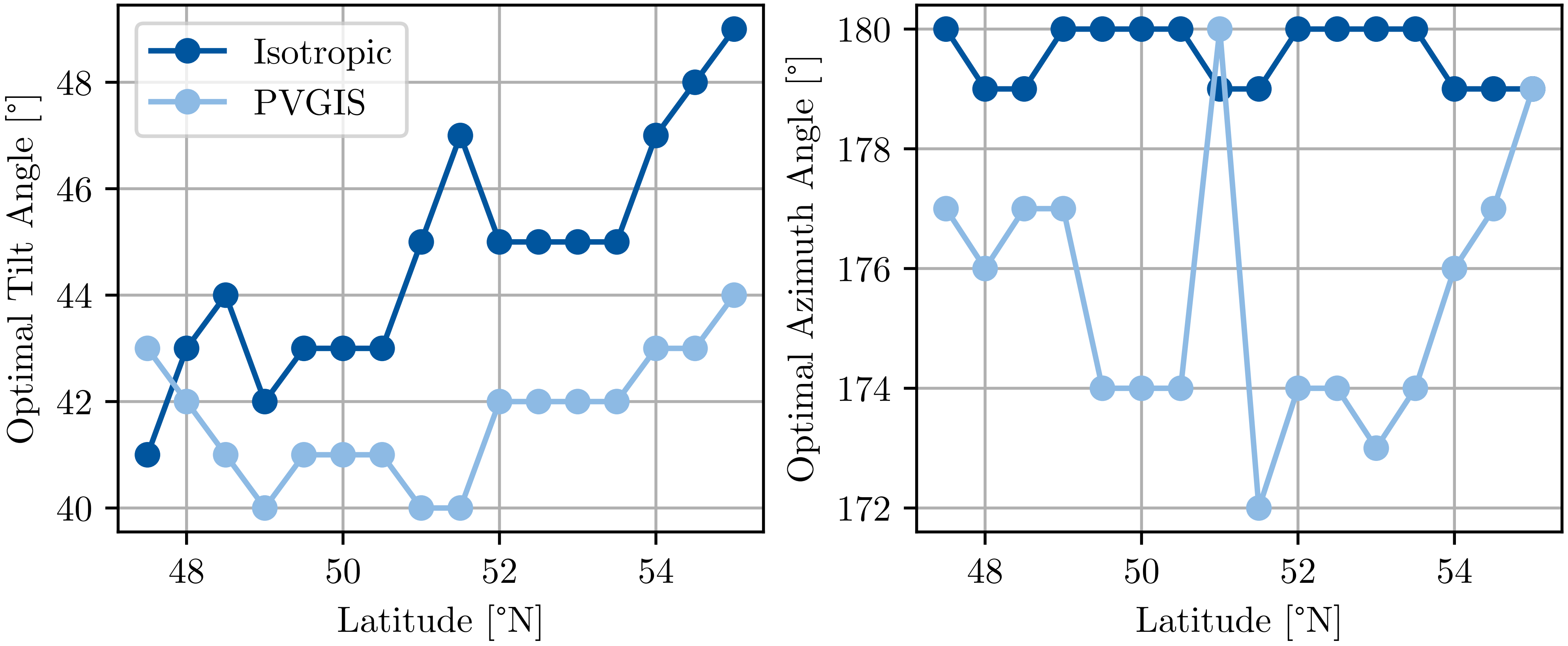
Conclusion

- Optimization framework for PV module orientation and inter-row gap
  - **Optimal orientation → highest POA irradiance**
    Perez transposition model and PVGIS irradiance data with bounded grid search
  - **Optimal inter-row gap**
    → highest POA irradiance/power output
    → lowest LCOE
    Self-shading, half-cut and cost model with power output simulation

Backup Slides

Optimal Module Orientation

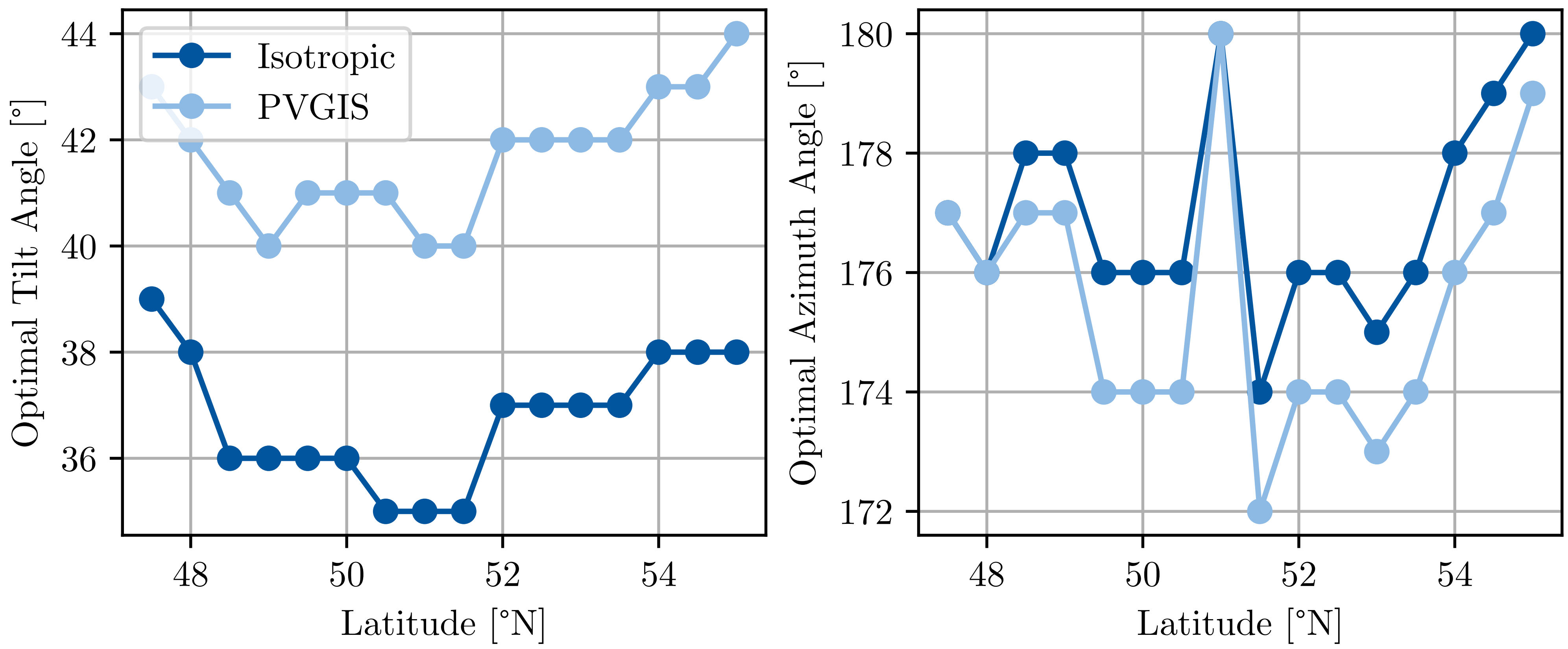
- Validate simulation results with PVGIS' optimal angles
- Isotropic sky model with clear sky model



- MAE: 3.375° tilt and 4.9375° azimuth

Optimal Module Orientation

- Validate simulation results with PVGIS' optimal angles
- Isotropic sky model with PVGIS irradiance data

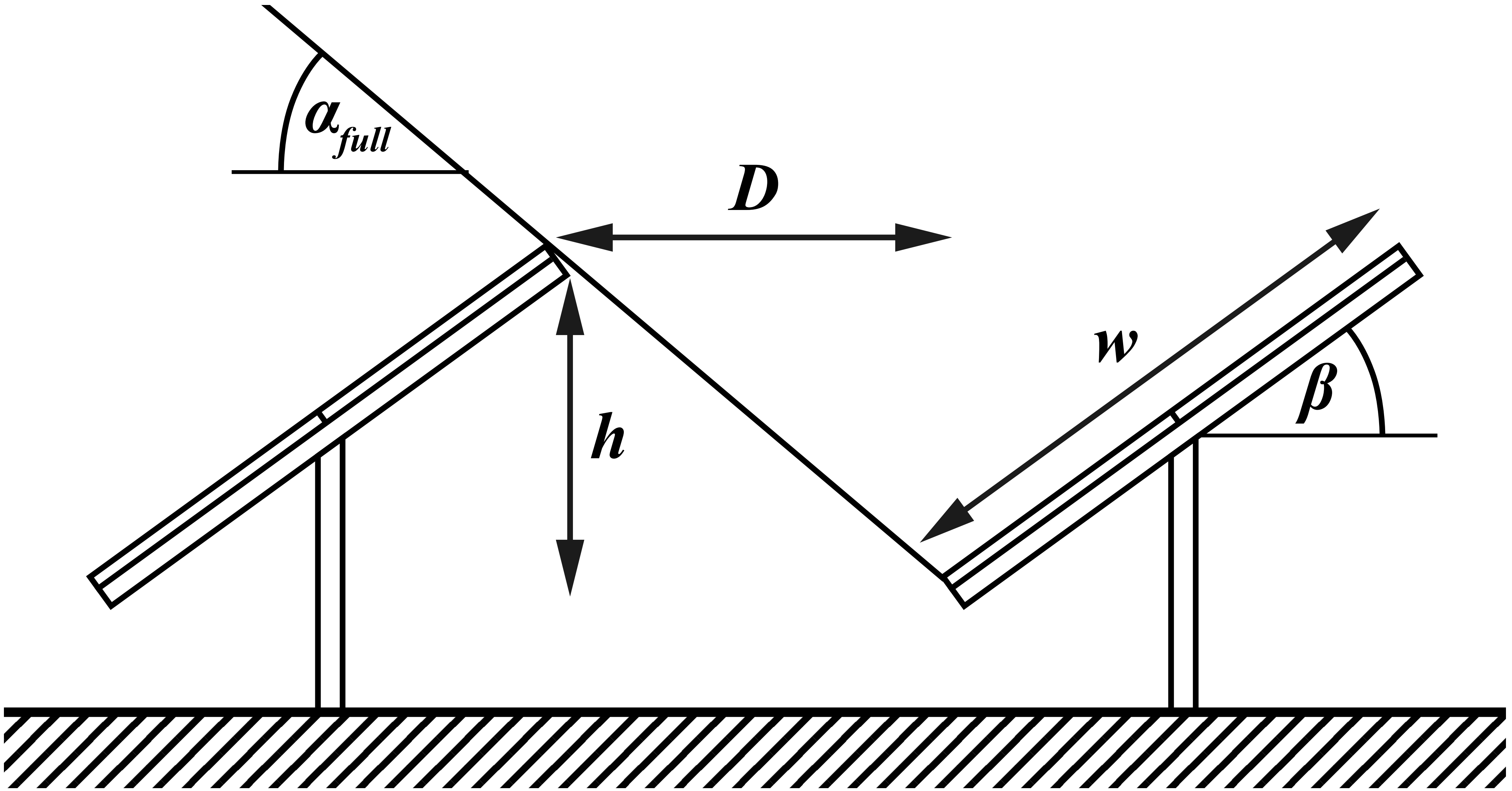


- MAE: 4.9375° tilt and 1.4375° azimuth

Self-Shading Model

Optimal Inter-Row Gap

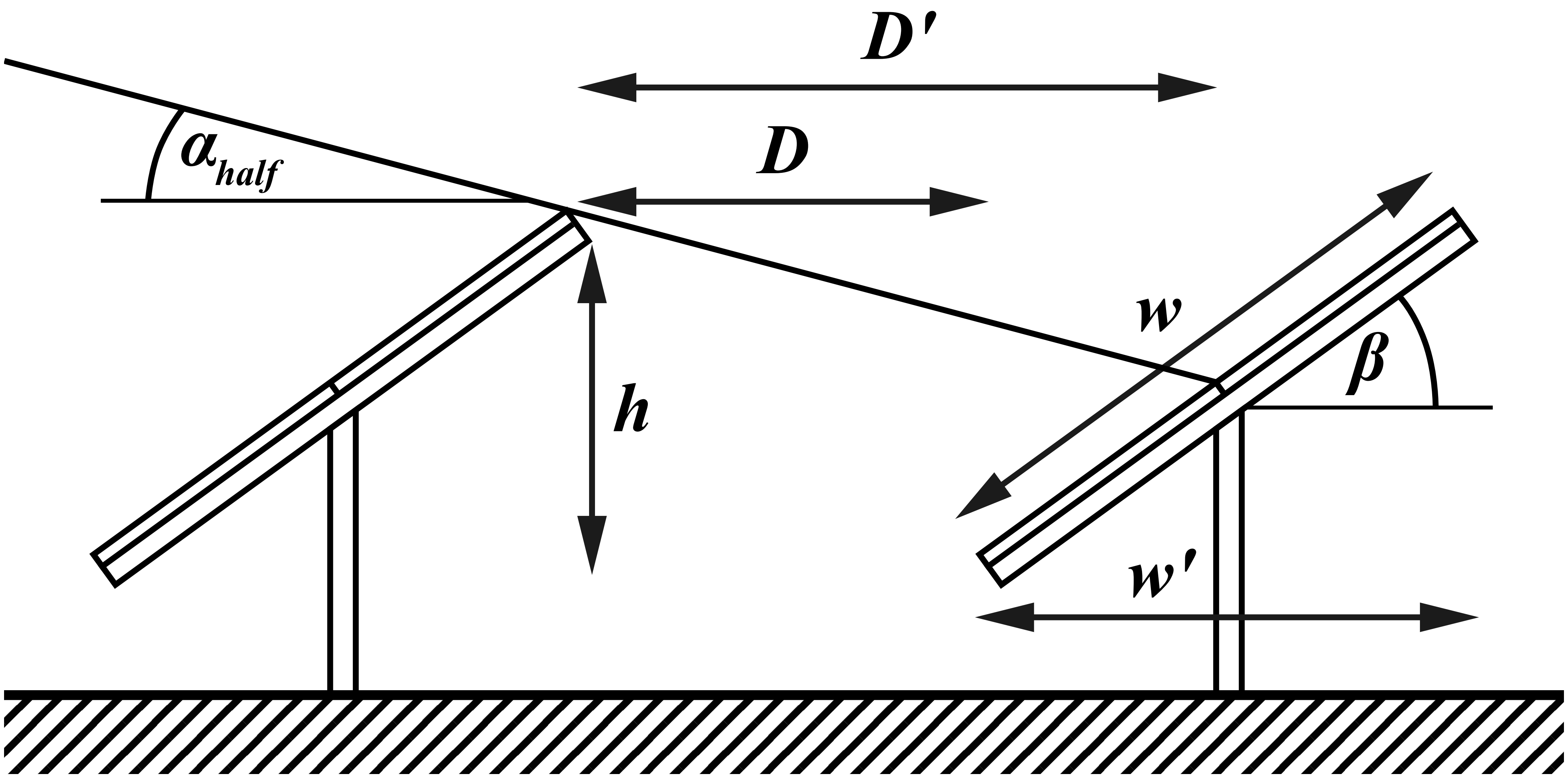
- $\alpha_{\text{full}} = \arccos \frac{h}{D} \qquad h = w \cdot \sin \beta$



Self-Shading Model

Optimal Inter-Row Gap

- $\alpha_{\text{half}} = \arccos \dfrac{h}{2 \cdot D'} \qquad D' = D + \dfrac{w'}{2} \qquad w' = w \cdot \sin\beta$



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