An approach to modeling linear and non-linear self-shading losses with pvlib

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Self-shade (row-to-row shade)

- About 40% of US utility-scale solar has self-shade losses
  - 25% thin-film tracking
  - 18% fixed tilt
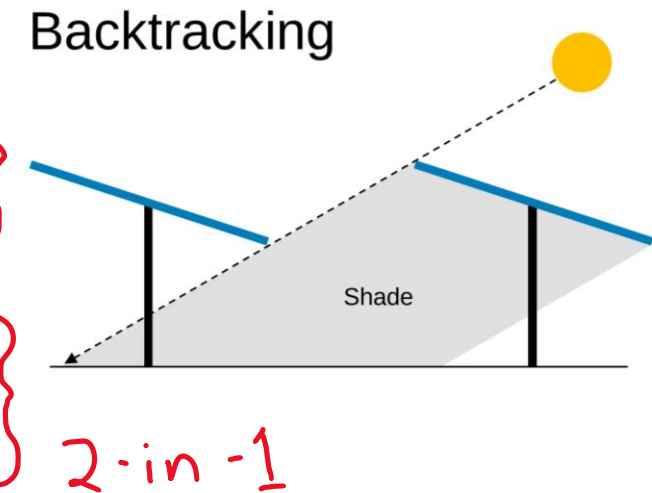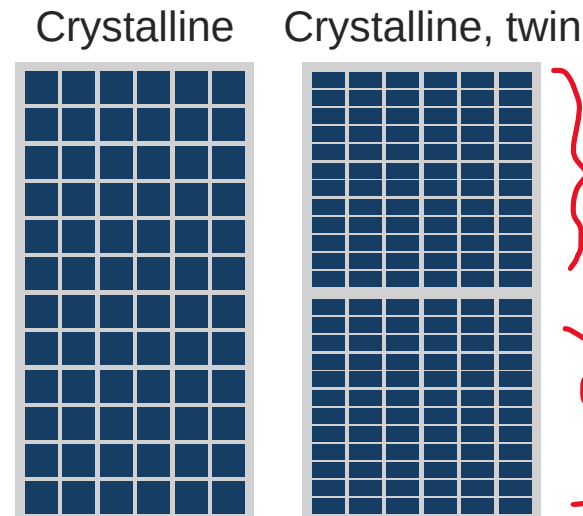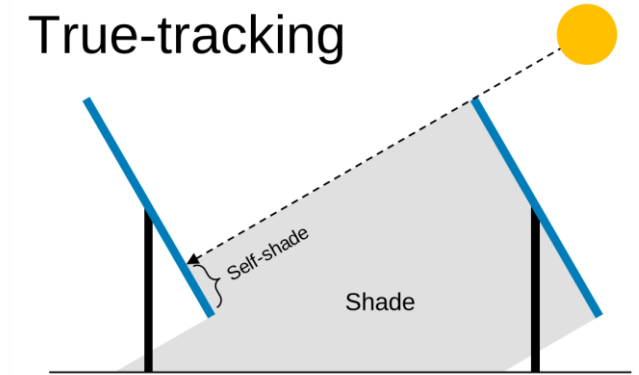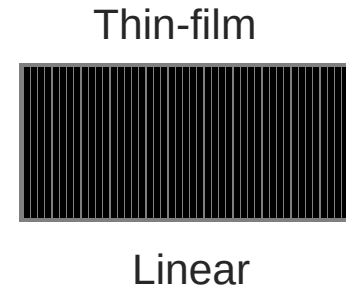   - 2/3 crystalline → 12% of solar has *non-linear* losses

How do we model all of this?
Non-linearity
Twin modules (w/ half-cut cells)?
Fractional backtracking?
Tracker issues?

Thin-film

Linear

True-tracking

Self-shade

Shade

Crystalline   Crystalline, twin   Backtracking

Shade

2-in-1

Non-Linear   Non-Linear

<hr />

2

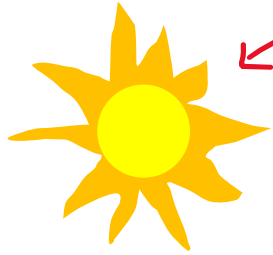Solar stats: Berkely Lab, Utility-Scale Solar 2023, at https://emp.lbl.gov/utility-scale-solar/

For example…

Easy to model:

ish
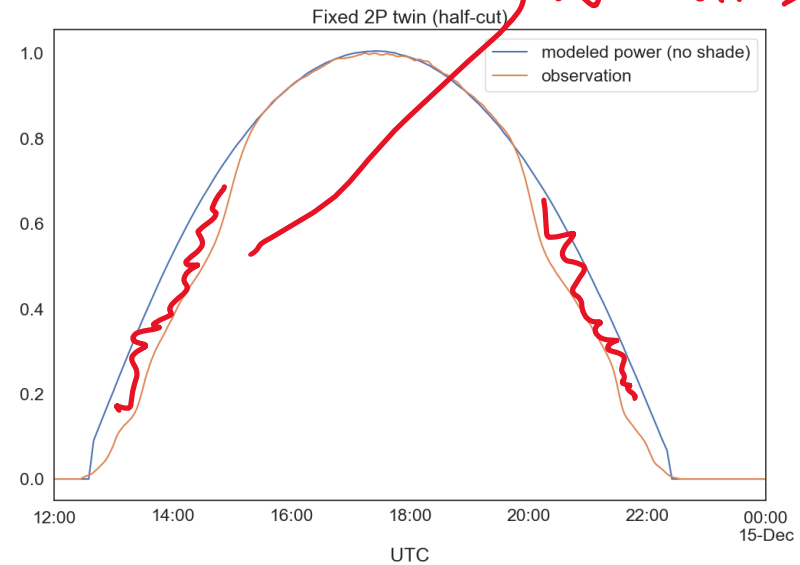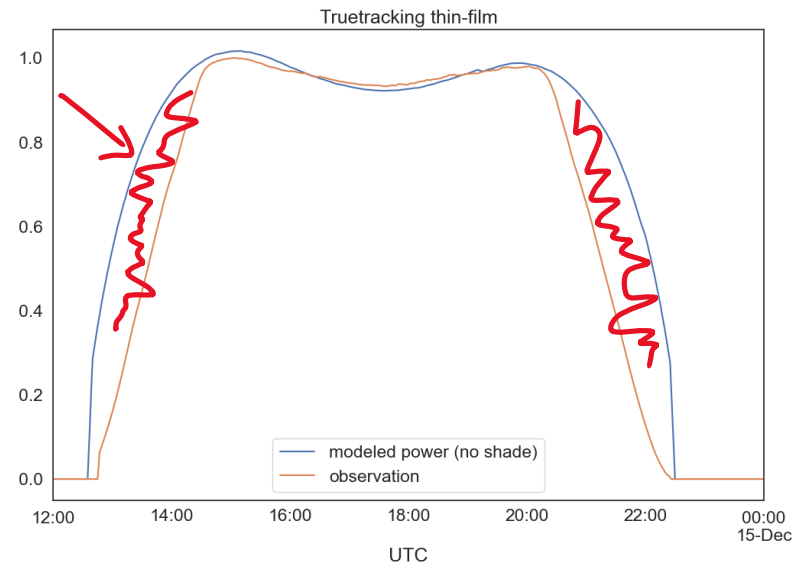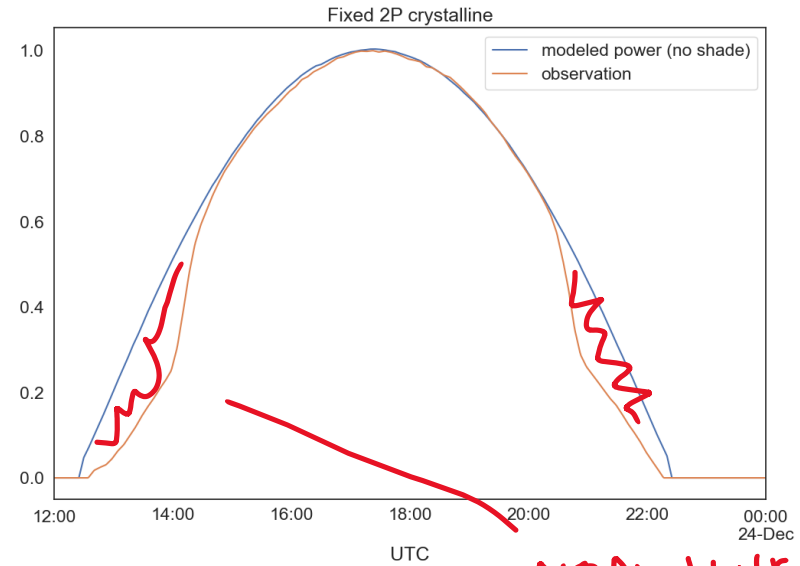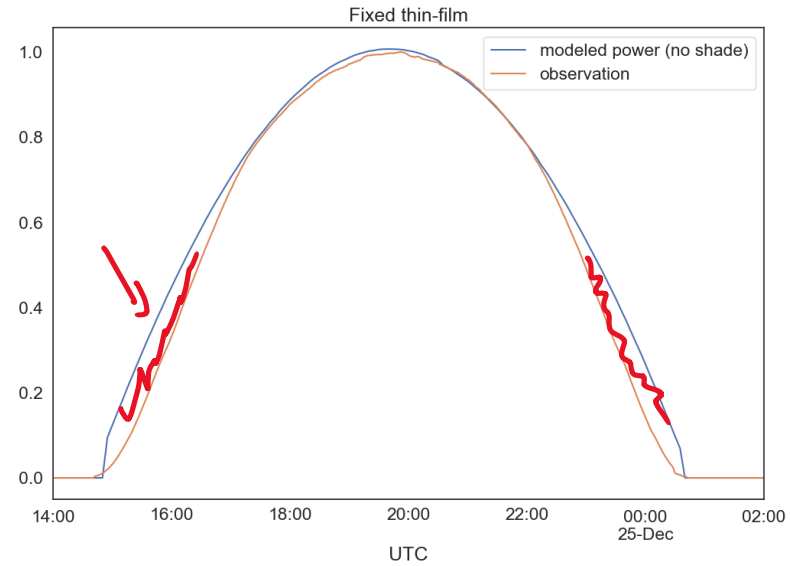
- Fixed crystalline w/ no shade

Hard~~er~~ to model

- Lower sun elevation = shade
- Non-linear losses
- 2P, 2P twin, etc…

What does this look like for power?

Overestimation at low sun angles:

Solution using pvlib

Steps:

1. Calculate shaded fraction*
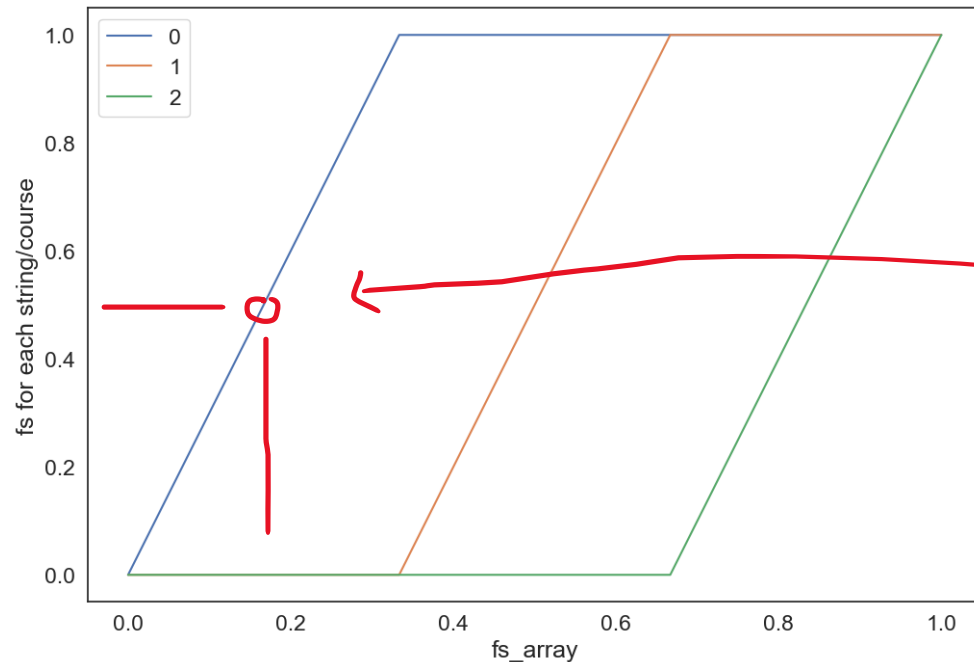2. Calculate power loss**
3. Done!

* Start with array shaded fraction, then calculate for each "course" (i.e., string) of modules

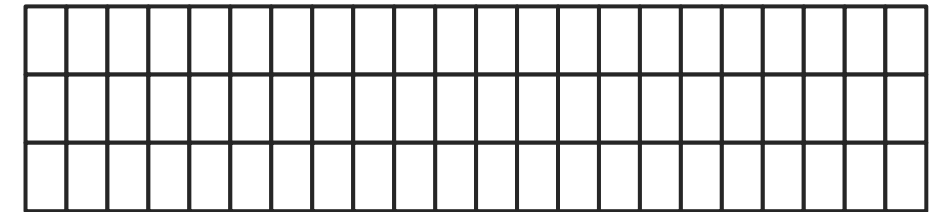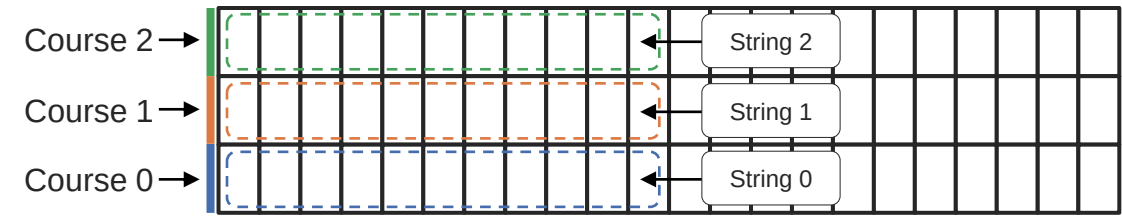** actually, effective irradiance instead of power loss

Shaded Fraction

- Use *shaded_fraction_front* from `infinite_sheds.get_irradiance()` for array shaded fraction

- Then calculate shaded fraction in each course*

* For our model, each string can only be in one course

Top-down view of 3P system (2 rows)

Course 2 →
String 2

Course 1 →
String 1

Course 0 →
String 0

End view of 3P system (2 rows)

Course 2 →

Course 1 →

Course 0 →

Shade
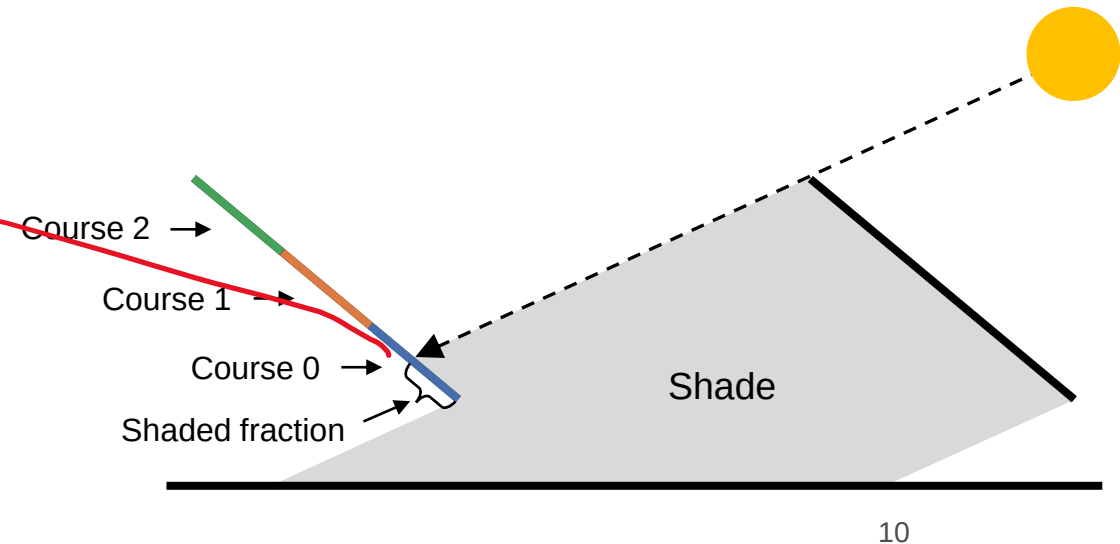
Shaded fraction

Twin modules?

- Double the number of effective modules up the side of a row
- For example, 2P twin → 4P effective
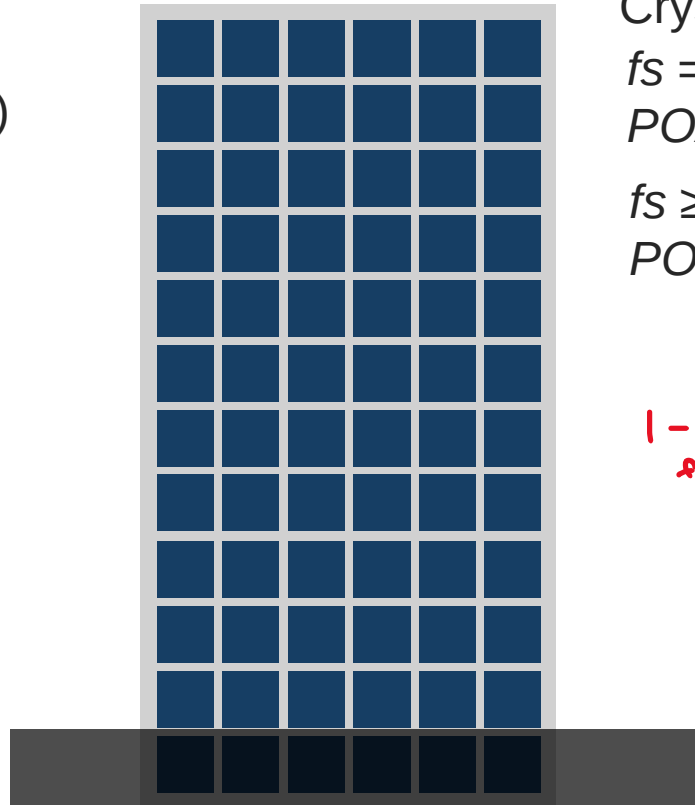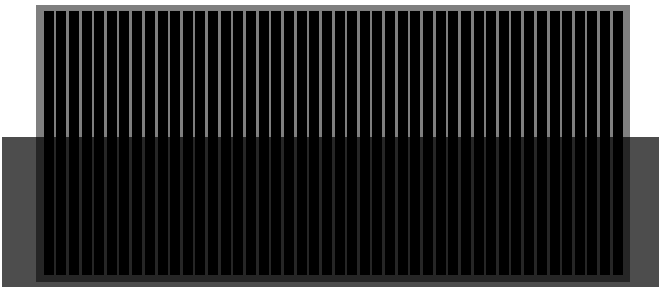
Calculate power (effective irradiance) loss

- Thin-film? Loss of direct irradiance linear with shaded fraction, *fs*
- Crystalline? Loss of direct irradiance *across the first row of cells*

(and treat twin modules as 2 modules)

Thin-film (linear):

$fs = 1/2$
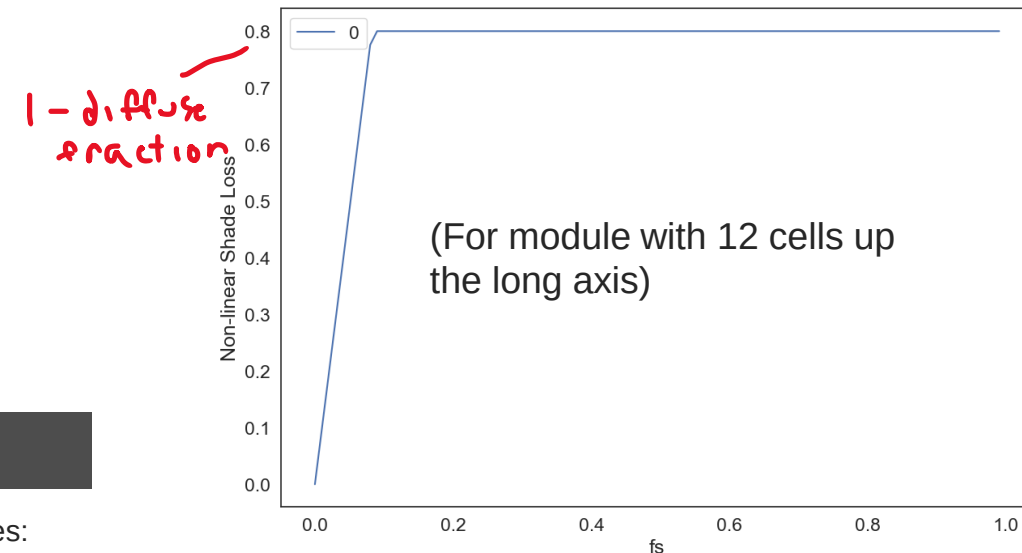POA_{direct} reduced by 1/2

Crystalline (non-linear):

$fs = 1/24$
POA_{direct} reduced by 1/2

$fs \geq 1/12$
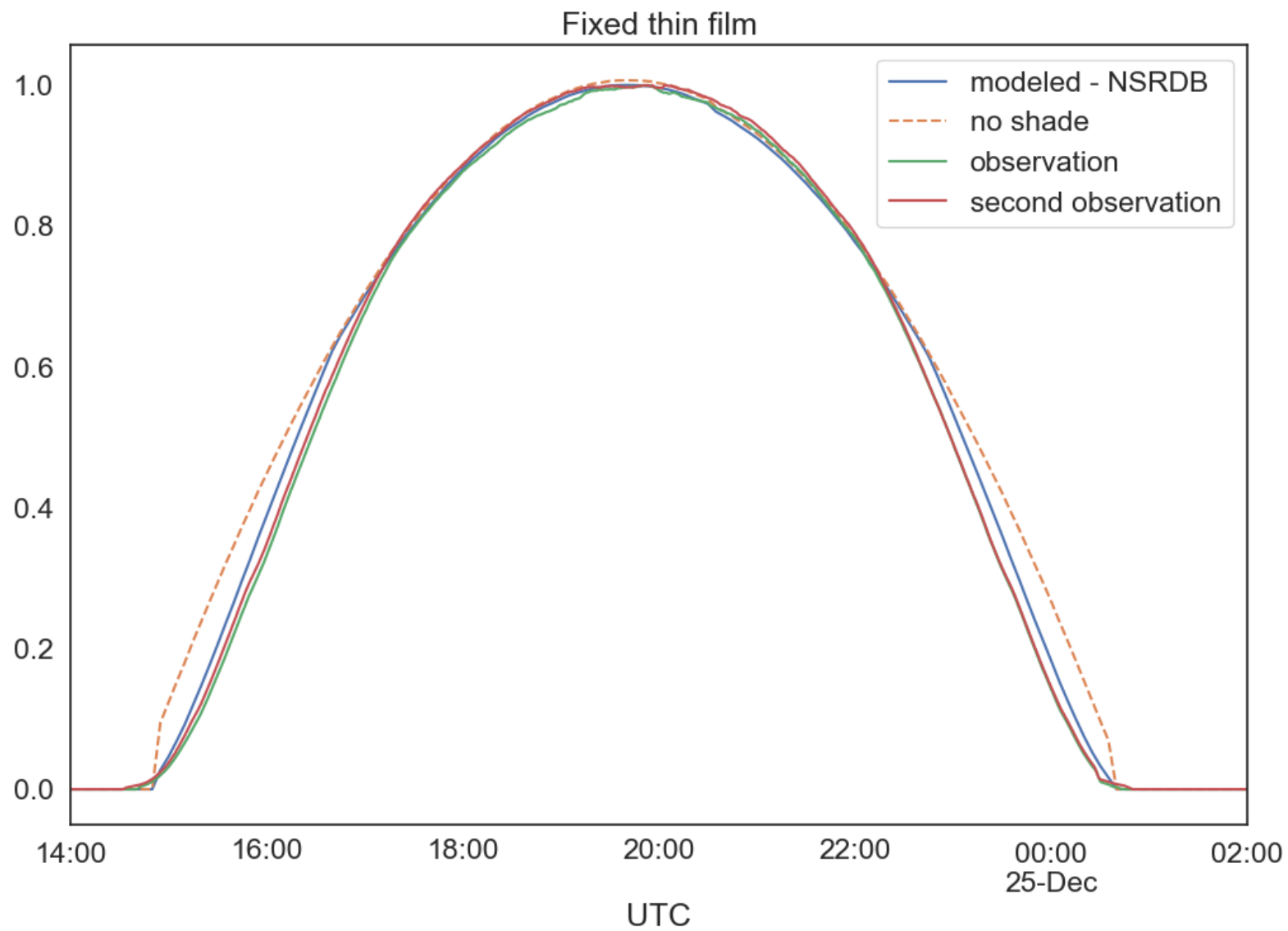POA_{direct} reduced by 100%

(handwritten in red) ½ of a cell

(handwritten in red) module is limited to cells w/ most shade (in portrait...)

(handwritten in red) 1-diffuse fraction

(For module with 12 cells up the long axis)

Non-linear Shade Loss

fs

Anderson, Kevin. 2020. Maximizing Yield with Improved Single-Axis Backtracking on Cross-Axis Slopes: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5K00-76023. https://www.nrel.gov/docs/fy20osti/76023.pdf.

Some results

with observations from 2 inverters per plant

Fixed thin film

1.6% annual difference (NSRDB)
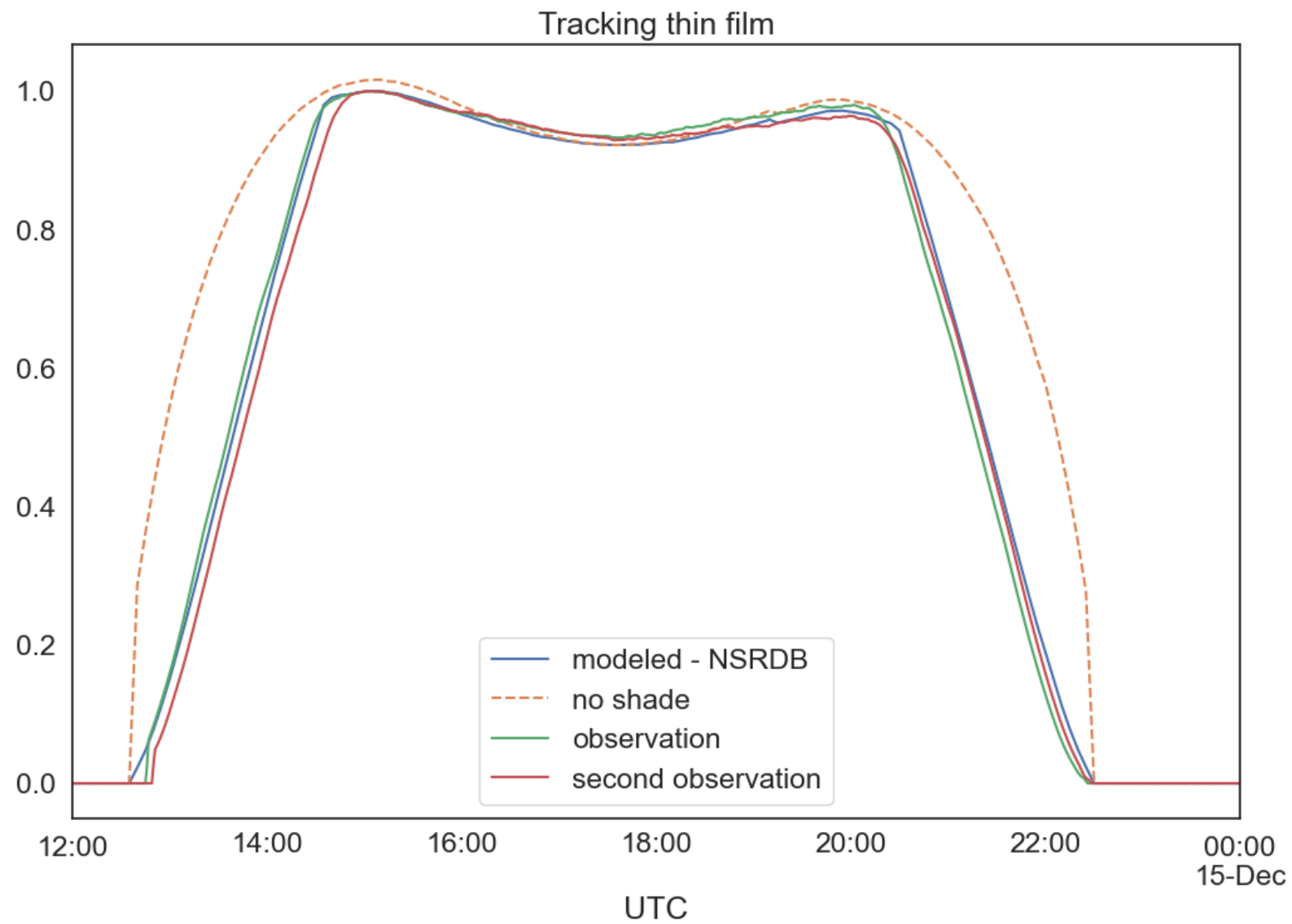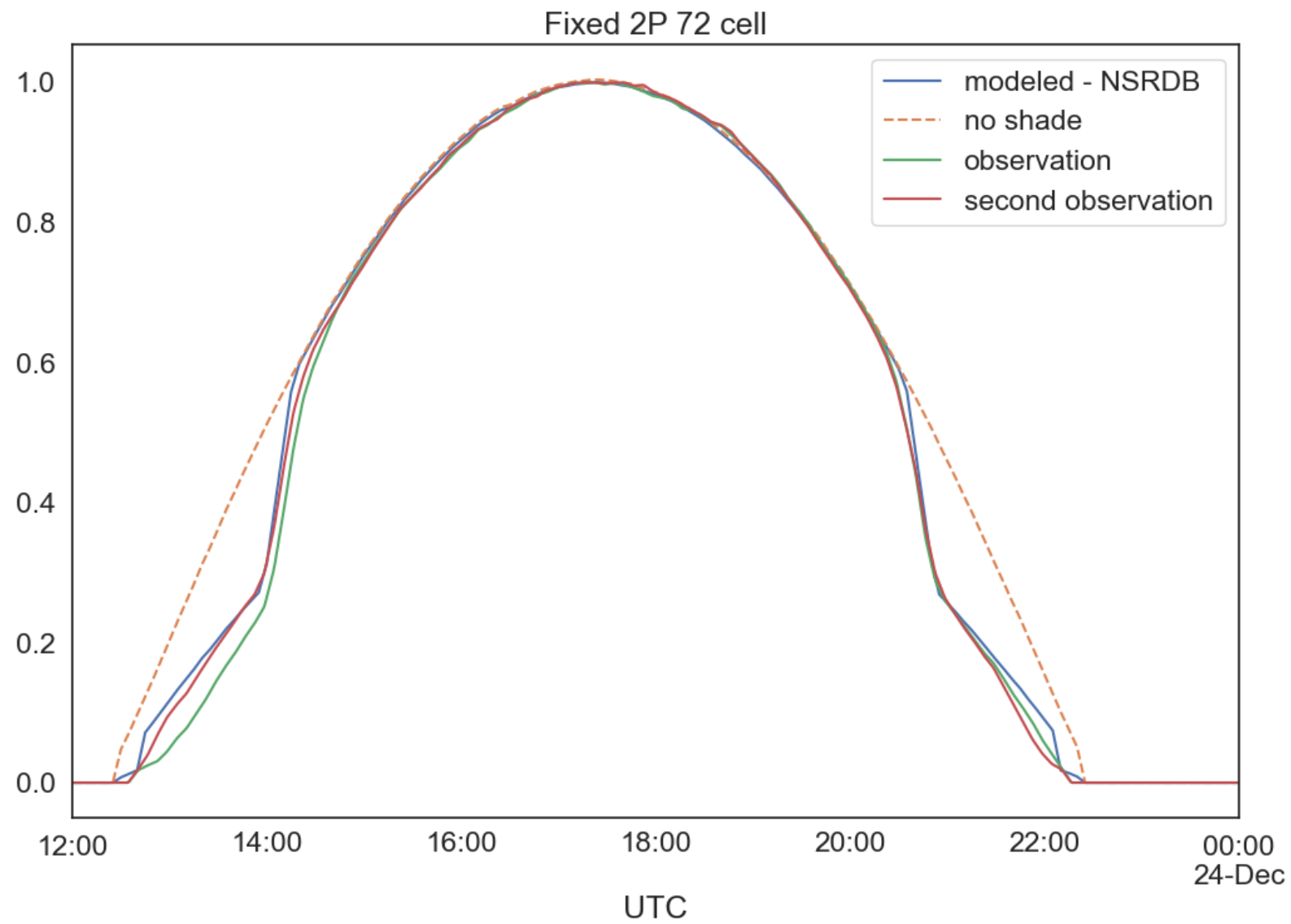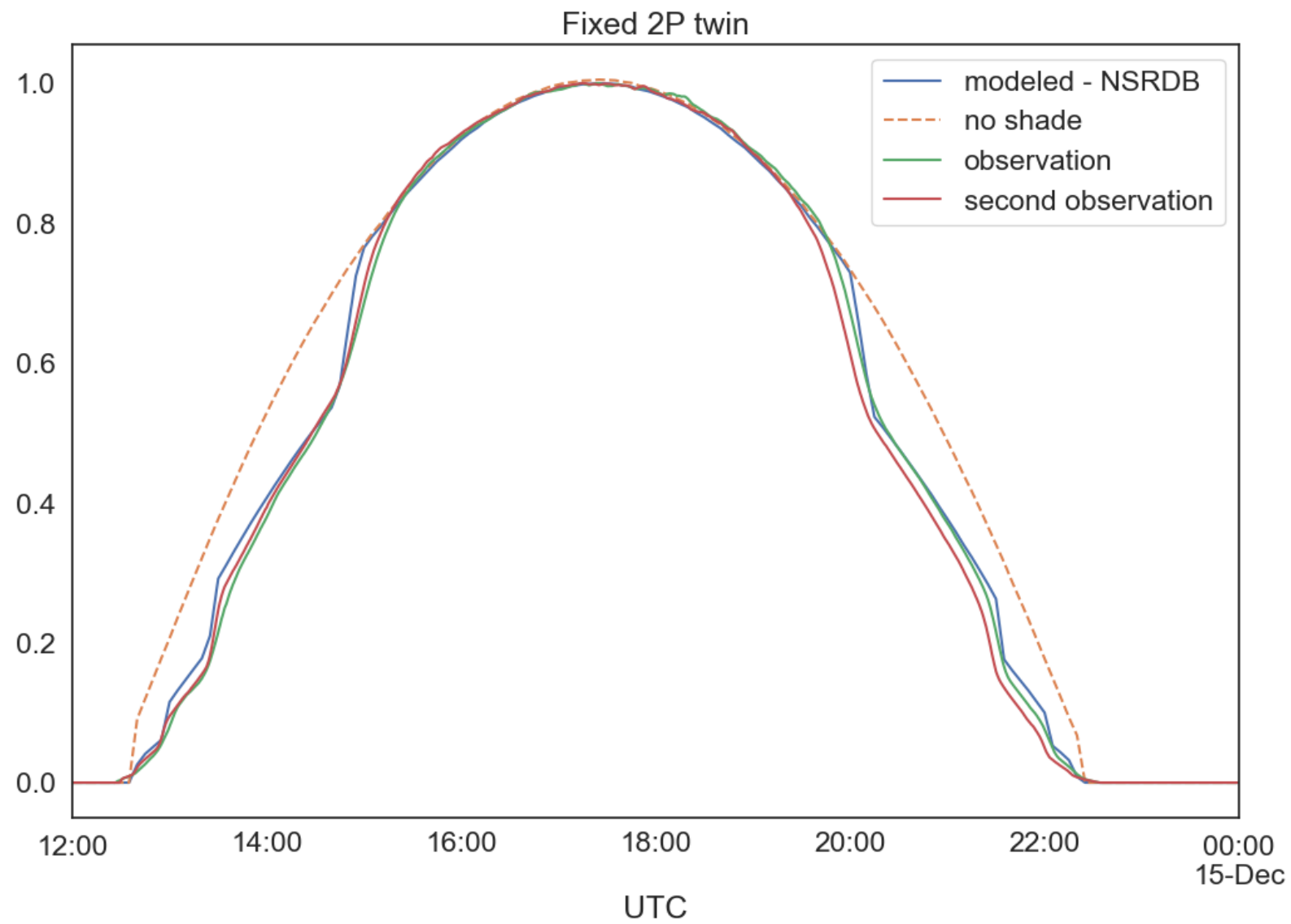
Tracking thin film

8.5% annual difference (NSRDB)

Fixed 2P 72 cell

1.9% annual
difference (NSRDB)

Fixed 2P twin

2.5% annual difference (NSRDB)

Fixed 2P 72 cell SW

2.7% annual difference (NSRDB)

Fixed thin film SW

2.3% annual difference (NSRDB)

Legend:
- modeled - NSRDB
- no shade
- observation
- second observation
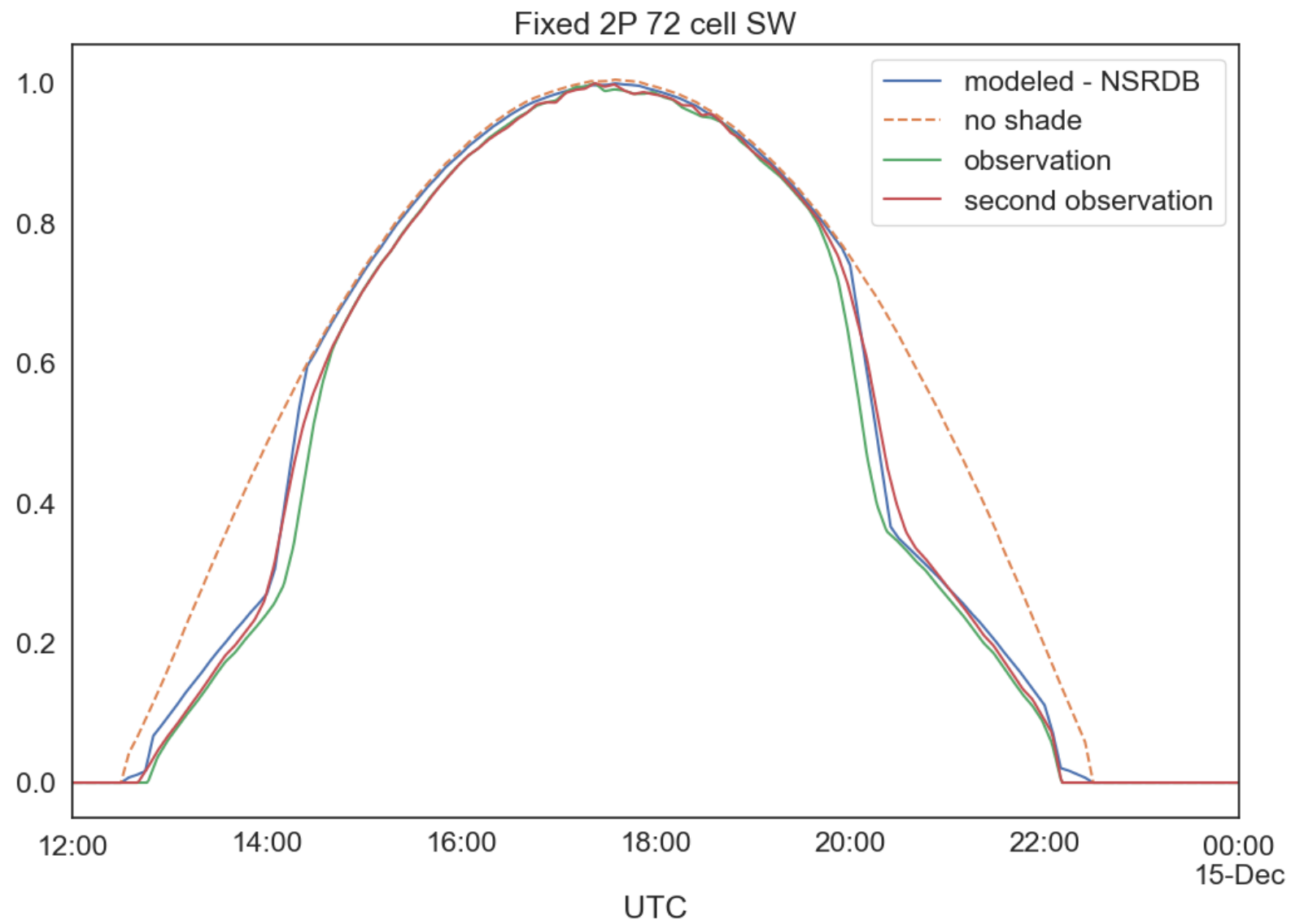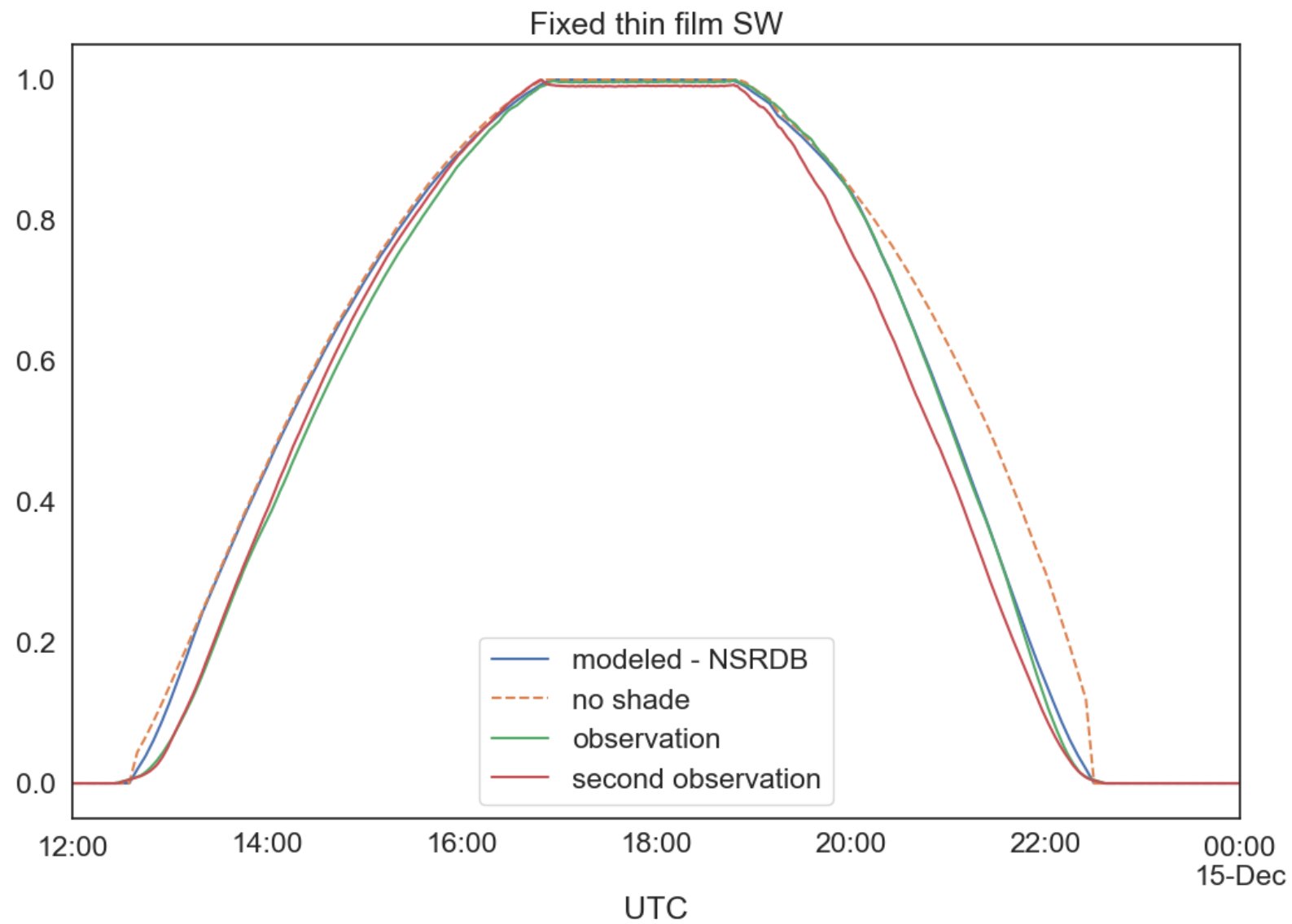
Back to the 2P twin plant

let's look at GCR

Fixed 2P twin

Legend:
- gcr=0.642
- gcr=0.65 ✓
- gcr=0.66
- observation
- second observation

Time (UTC)
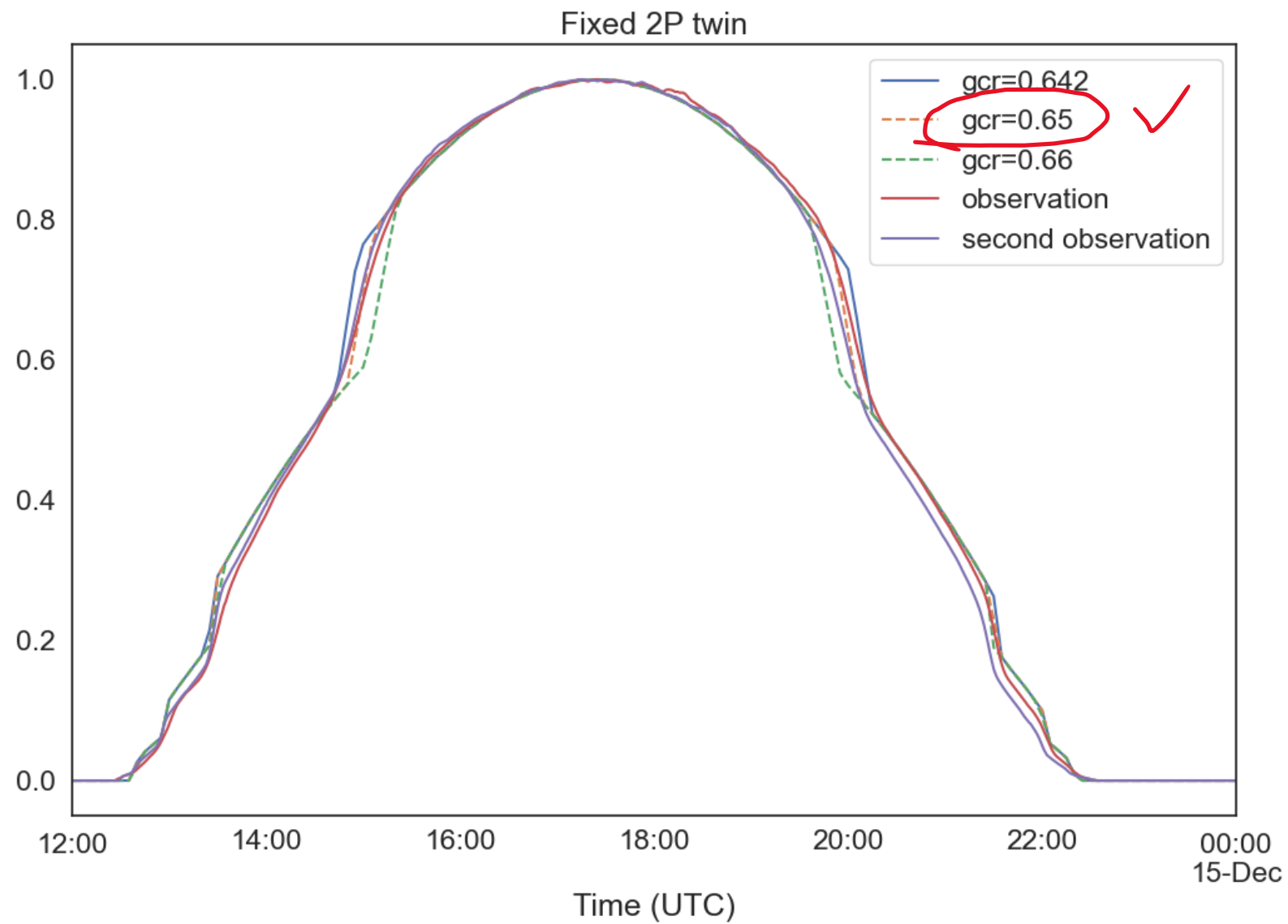
Let's look at the steps
zoom in on the morning

Fixed 2P twin

Fixed 2P twin

Legend:
- model
- no shade
- observation
- fs 0
- fs 1
- fs 2
- fs 3
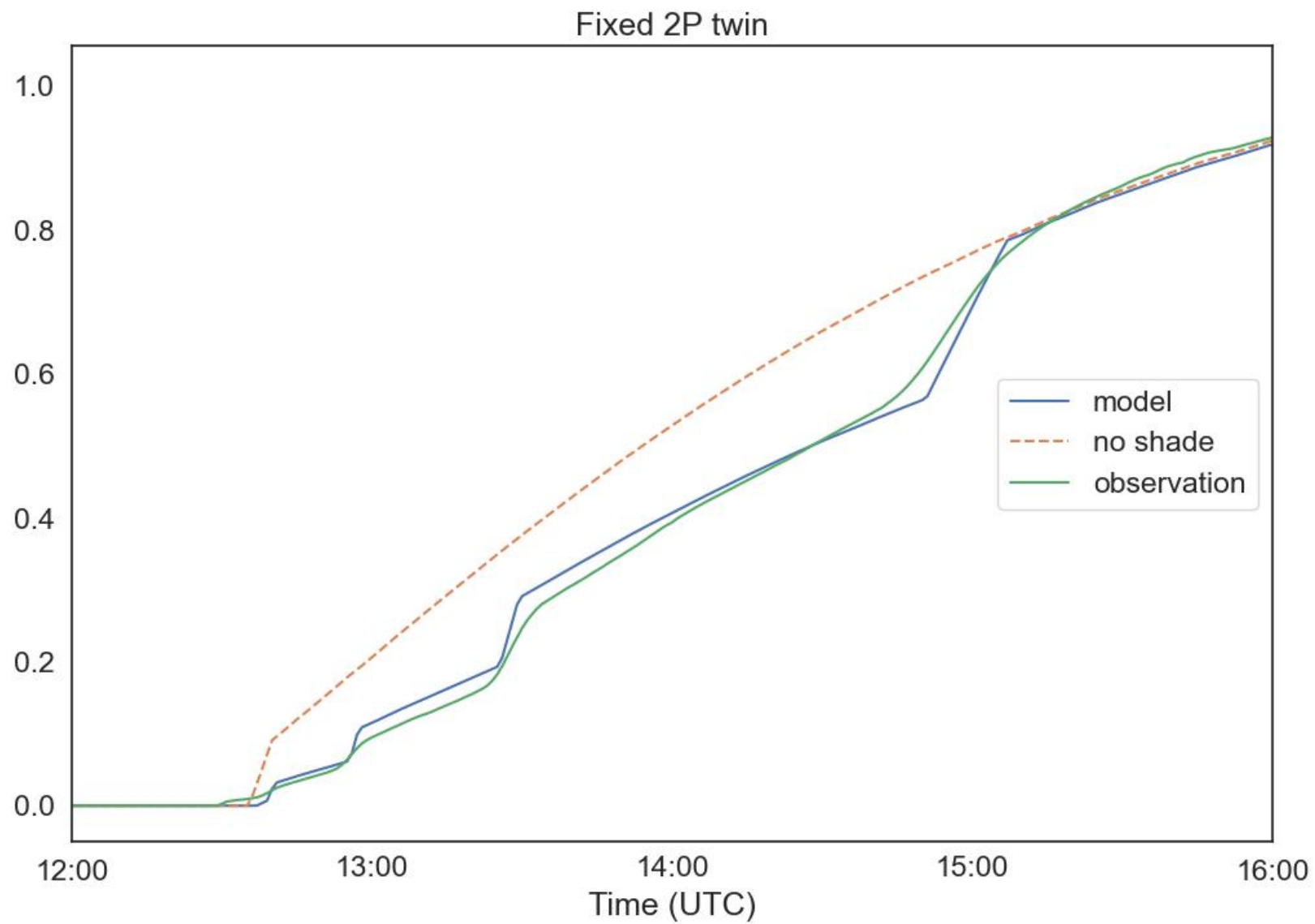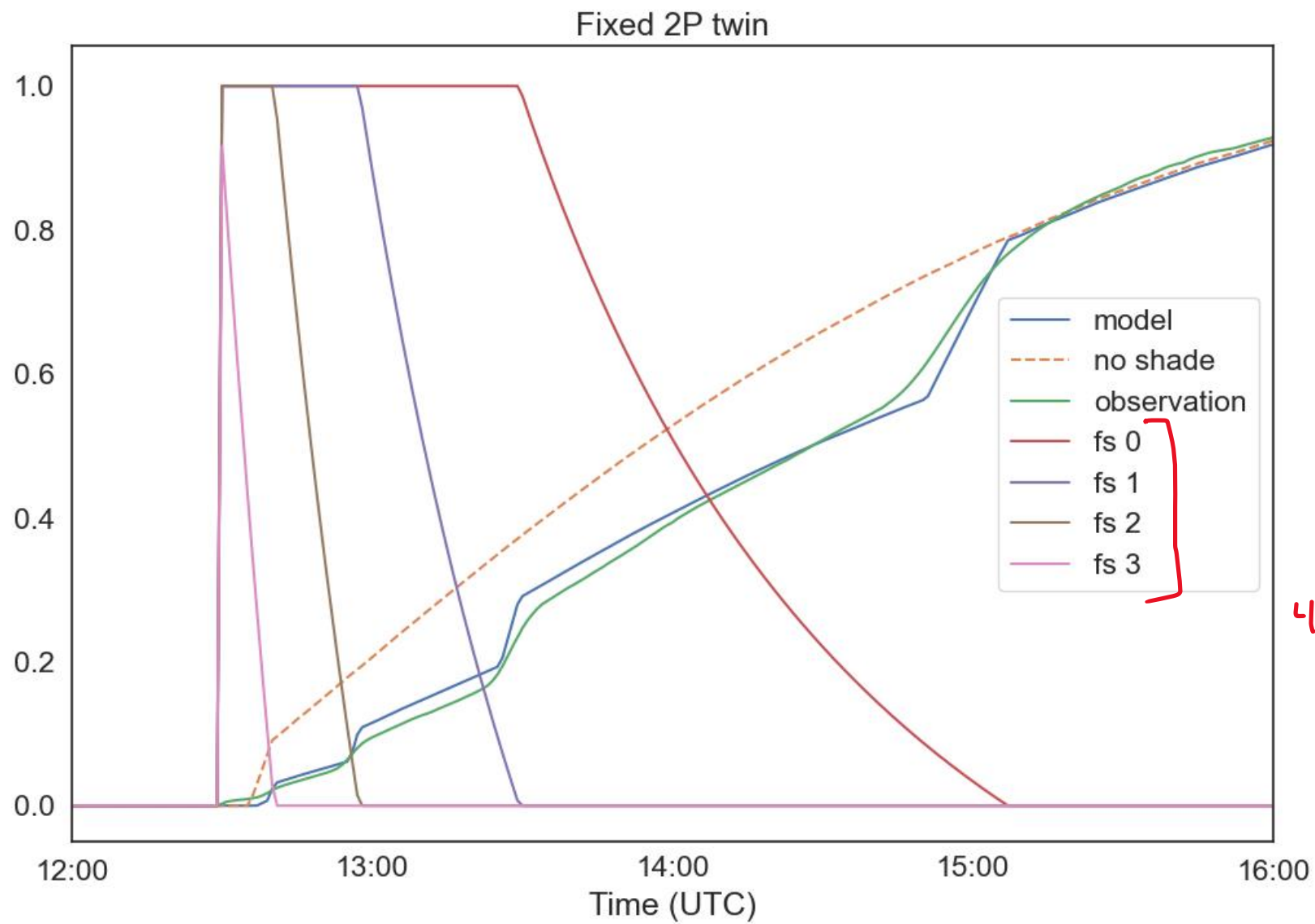
4 effective courses b/c twin

24

Fixed 2P twin

$f_s = 0$

$\hat{f_s} = 1/12$*

model
no shade
observation
fs 0
fs 1
fs 2
fs 3

* modules have 24 cells up, so 2× effective 12 cells

Time (UTC)
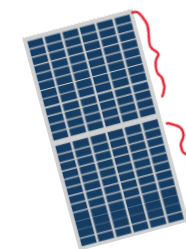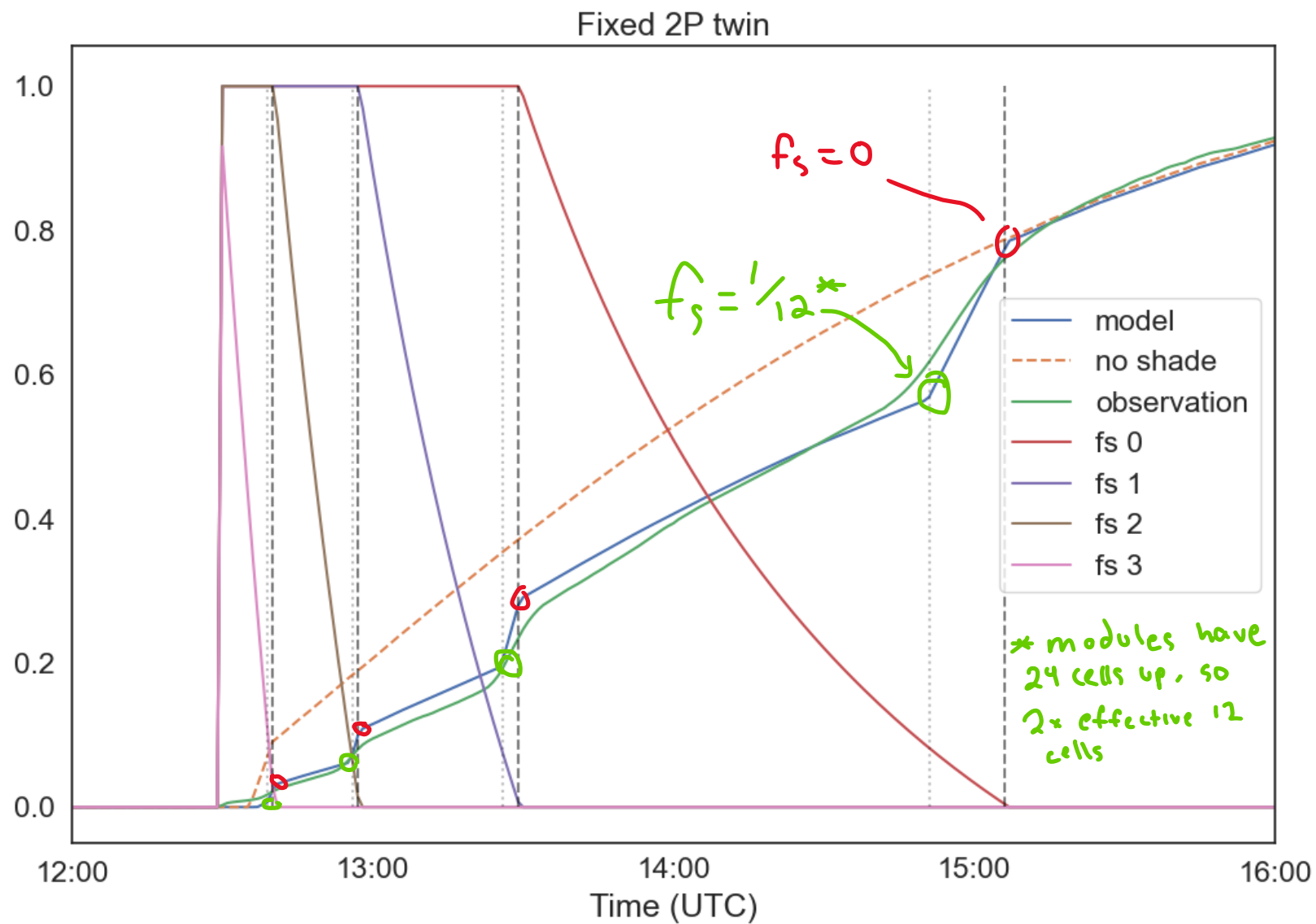
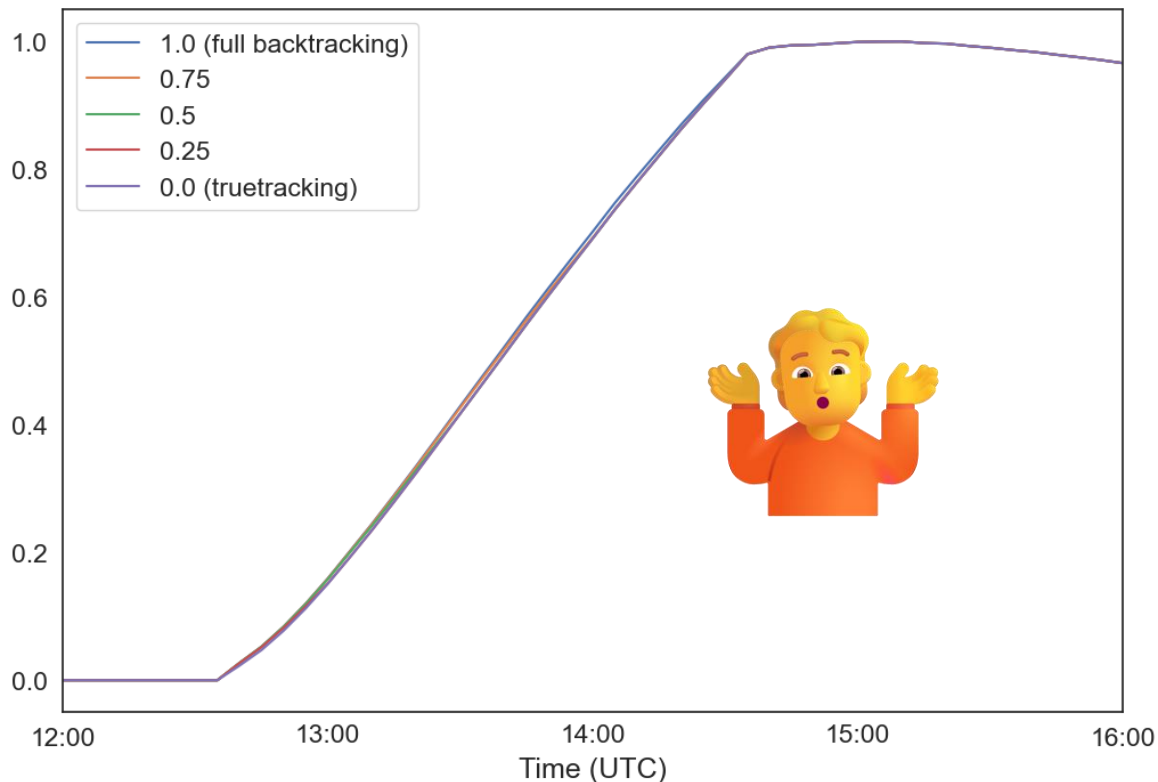# Other applications

fractional backtracking,
backtracking faults

Fractional Backtracking

- For twin modules, especially 2P (effectively 4P conventional) backtracking to allow shade for a fraction of the array might make sense (maybe even truetracking)

- Let's model a 2P twin example:

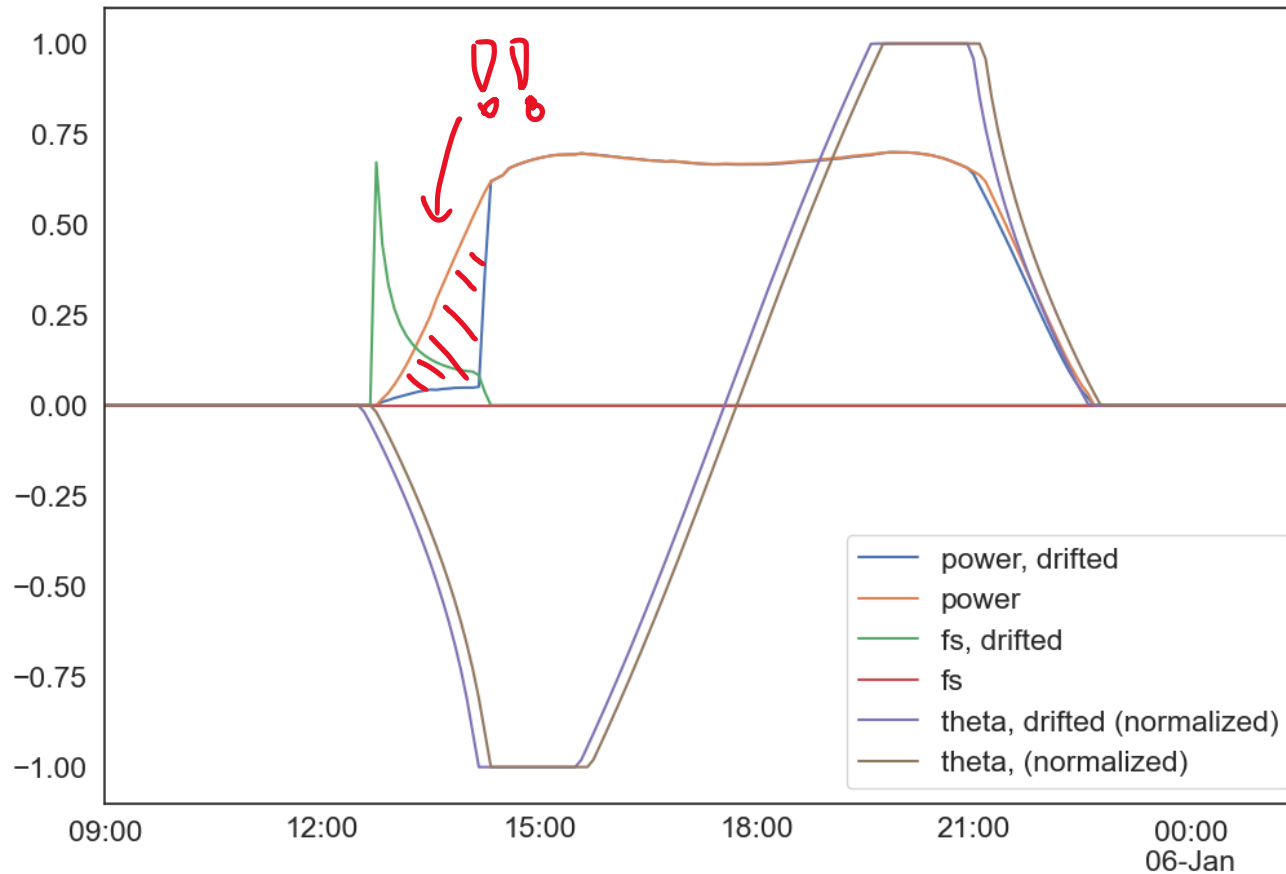| Mode	Annual Energy kWh (NSRDB)
Full backtracking (1.0)	2058
0.75 backtracking	2050
0.5 backtracking	2046
0.25 backtracking	2044
0.0 (truetracking)	2043

Resource -dependent ??

Misaligned trackers (clock drift)

- Tracker clock is 10 minutes fast
- 1P 72-cell crystalline

~5% annual losses!
(NSRDB)

Code availability

it's open-source!

https://github.com/williamhobbs/2024_pvpmc_self_shade

Repo includes everything shown here:

- Functions
- example notebooks with plots
- anonymized observation data and specs

Functions

- shade_fractions(fs_array, eff_row_side_num_mods)

- non_linear_shade(n_cells_up, fs, fd)

- plant_power_with_shade_losses(
    resource_data,
    **plant_data,   ← *Dictionary of specs*
    surface_tilt_timeseries,
    surface_azimuth_timeseries,   } *Optional*
    use_measured_poa,
    use_measured_temp_module)

(https://github.com/williamhobbs/
pv-plant-specifications)

INCLUDES BIFACIAL!!

Questions?

whobbs@southernco.com

https://github.com/williamhobbs/2024_pvpmc_self_shade