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# SAM Webinars 2017: Modeling Molten Salt Power Tower Systems in SAM 2017.1.17

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May 18, 2017

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# SAM Webinars 2017

- Overview of New Industrial Process Heat and CSP Capabilities, May 17
- **Modeling Molten Salt Power Tower Systems, May 18**
- Electricity Rates and Monthly Bill Savings for Residential and Commercial Projects, June 1
- Modeling PV-Battery Systems, July 13
- Sizing Photovoltaic Systems, August 10
- SAM Open Source, September 21

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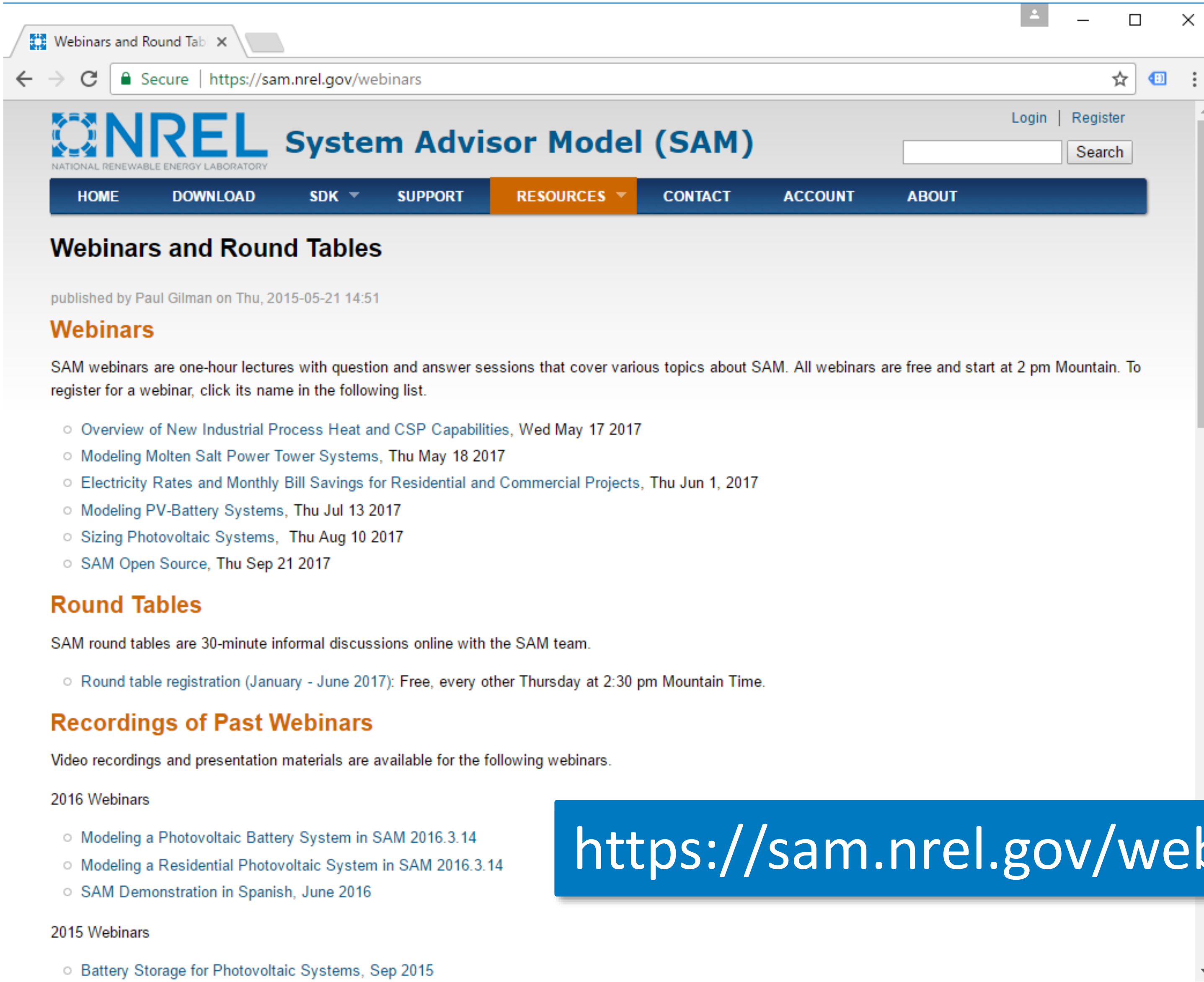
Webinars and Round Tab

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## Webinars and Round Tables

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### Webinars

SAM webinars are one-hour lectures with question and answer sessions that cover various topics about SAM. All webinars are free and start at 2 pm Mountain. To register for a webinar, click its name in the following list.

- Overview of New Industrial Process Heat and CSP Capabilities, Wed May 17 2017
- Modeling Molten Salt Power Tower Systems, Thu May 18 2017
- Electricity Rates and Monthly Bill Savings for Residential and Commercial Projects, Thu Jun 1, 2017
- Modeling PV-Battery Systems, Thu Jul 13 2017
- Sizing Photovoltaic Systems, Thu Aug 10 2017
- SAM Open Source, Thu Sep 21 2017

### Round Tables

SAM round tables are 30-minute informal discussions online with the SAM team.

- Round table registration (January - June 2017): Free, every other Thursday at 2:30 pm Mountain Time.

### Recordings of Past Webinars

Video recordings and presentation materials are available for the following webinars.

2016 Webinars

- Modeling a Photovoltaic Battery System in SAM 2016.3.14
- Modeling a Residential Photovoltaic System in SAM 2016.3.14
- SAM Demonstration in Spanish, June 2016

2015 Webinars

- Battery Storage for Photovoltaic Systems, Sep 2015

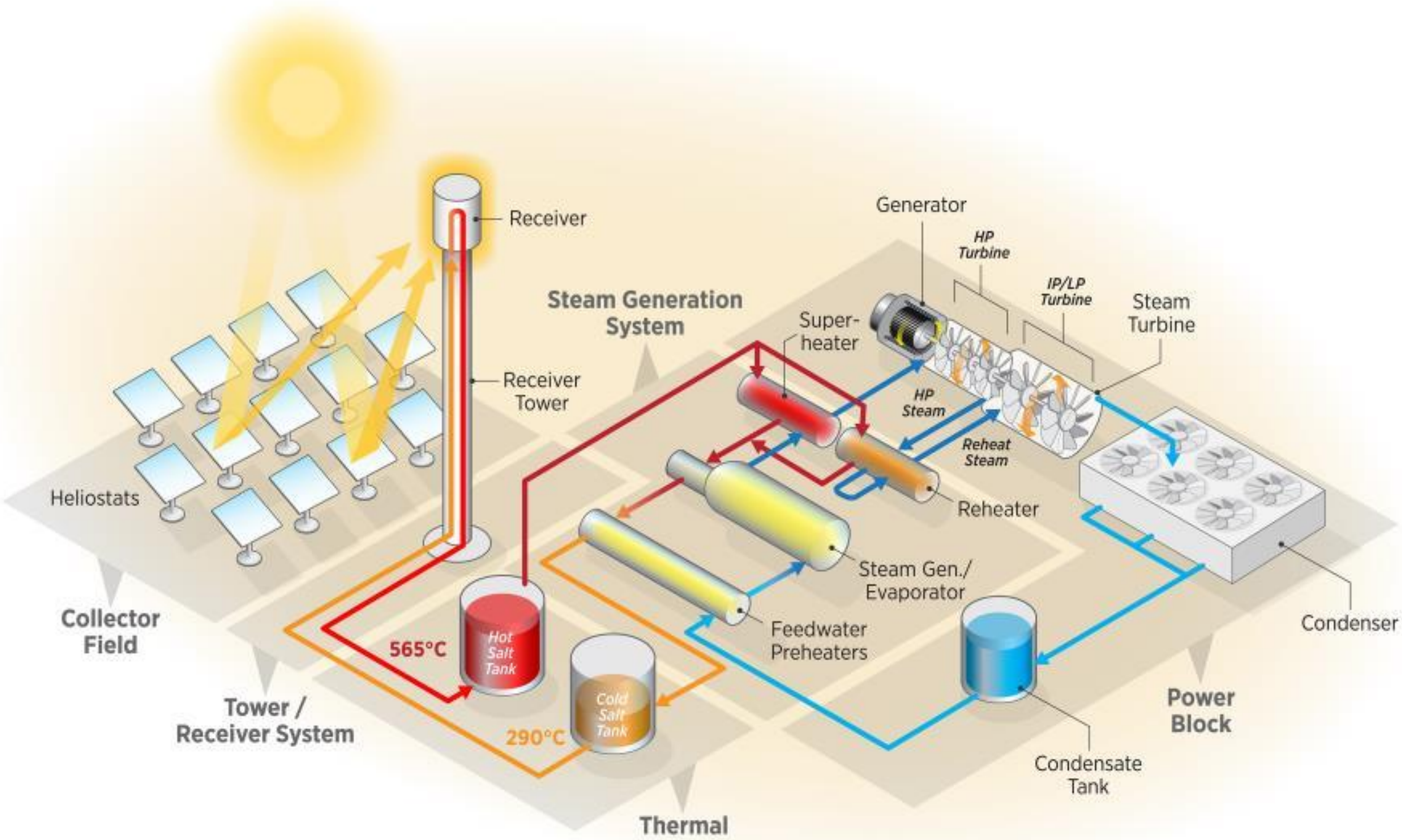
https://sam.nrel.gov/webinars

# Outline

- Model updates and improvements
- Demo
  - Design point DNI
  - Optimizing solar field geometry
  - Dispatch optimization
- Question & Answer (20 minutes)

# Model updates and improvements

# System description

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# How SAM models MSPT systems

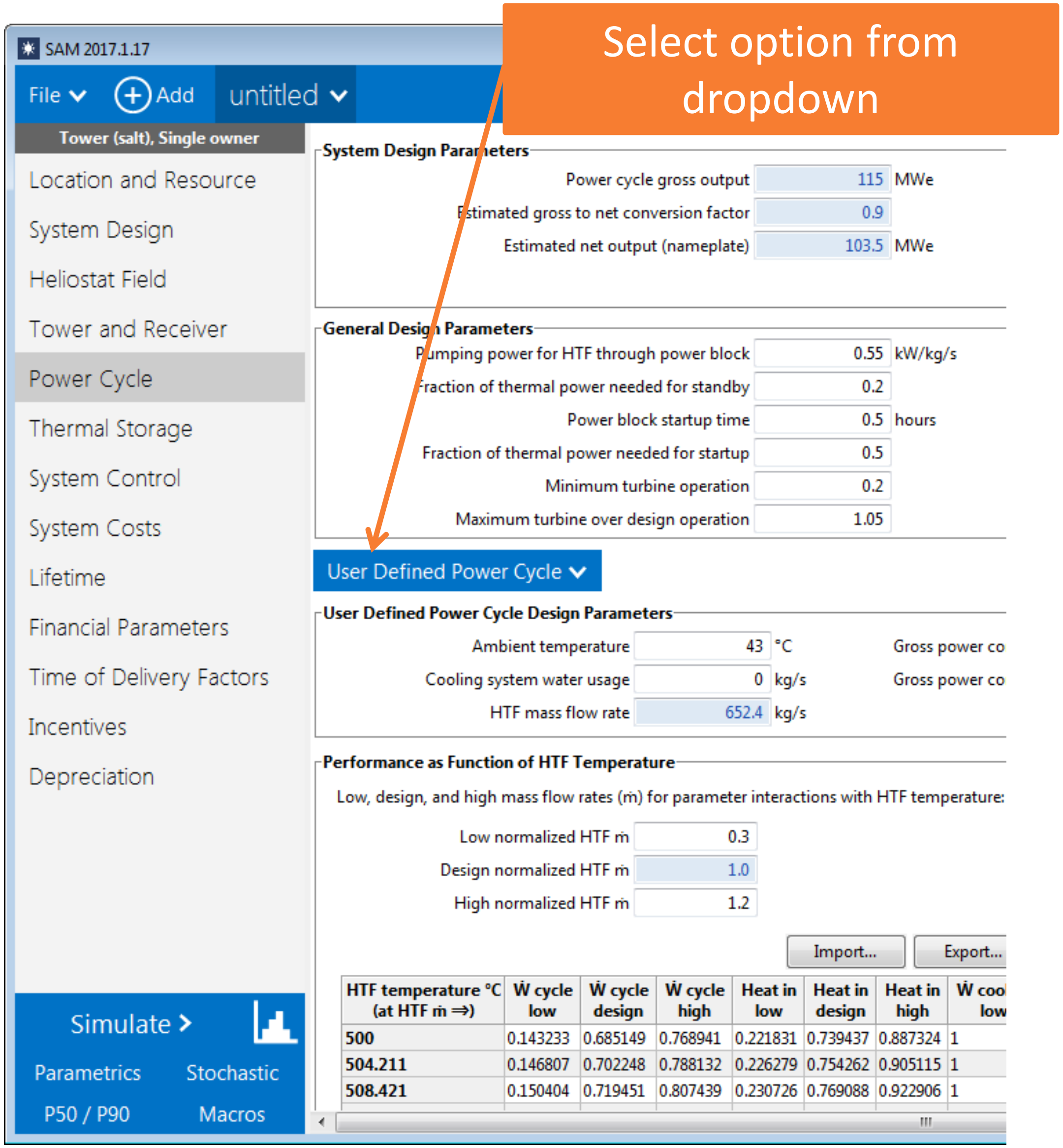
1. Design stage
    - Optimization
    - Final layout
2. Optical characterization
3. Performance simulation
    - Plant operations schemes: heuristic dispatch or optimized dispatch

# Updates and improvements

- User-defined power cycle
- Dispatch optimization
- Hourly time-of-dispatch factors
- Improved solar field performance availability specification
- User specification of attenuation loss coefficients

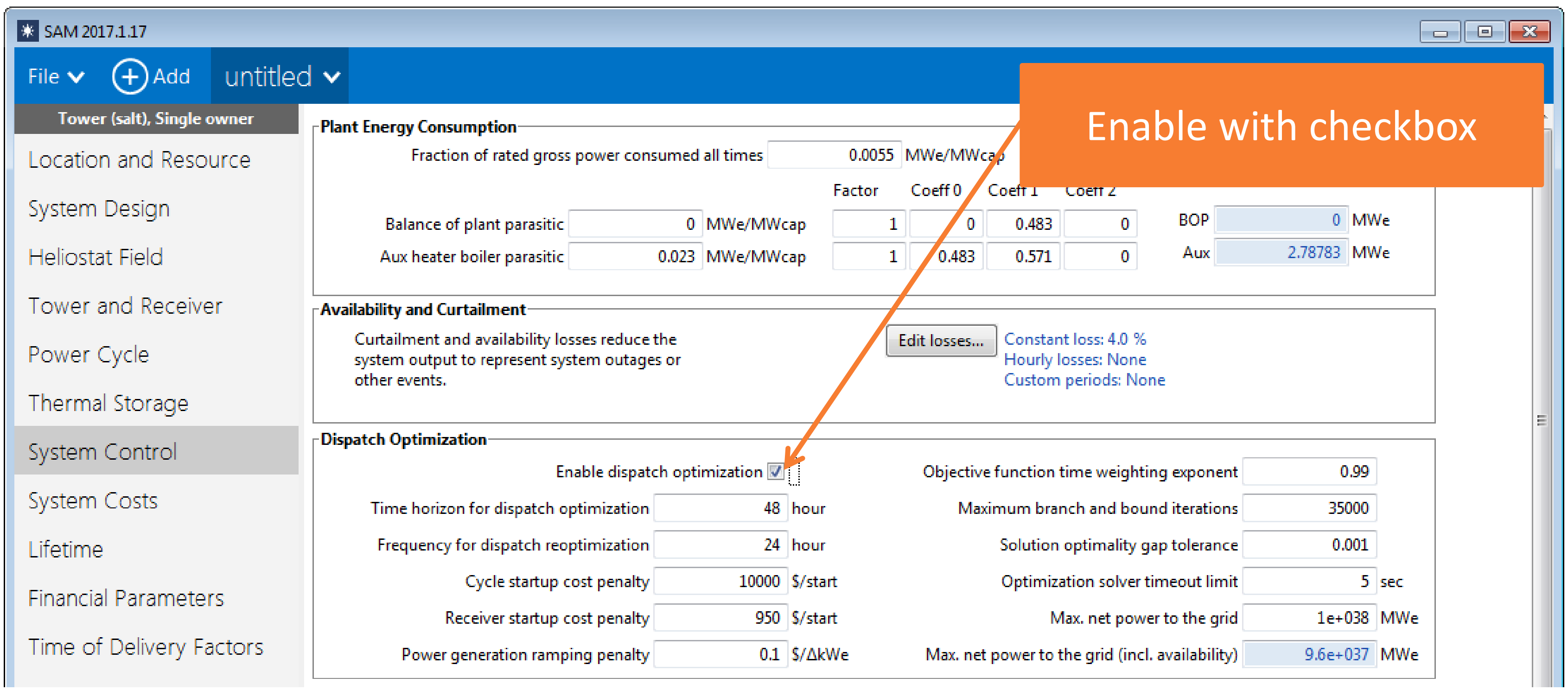
# User-defined power cycle

- Allows specification of detailed performance of a custom cycle
- Performance depends on:
    - HTF mass flow
    - HTF temperature
    - Ambient temperature
- Interactions between variables can be modeled

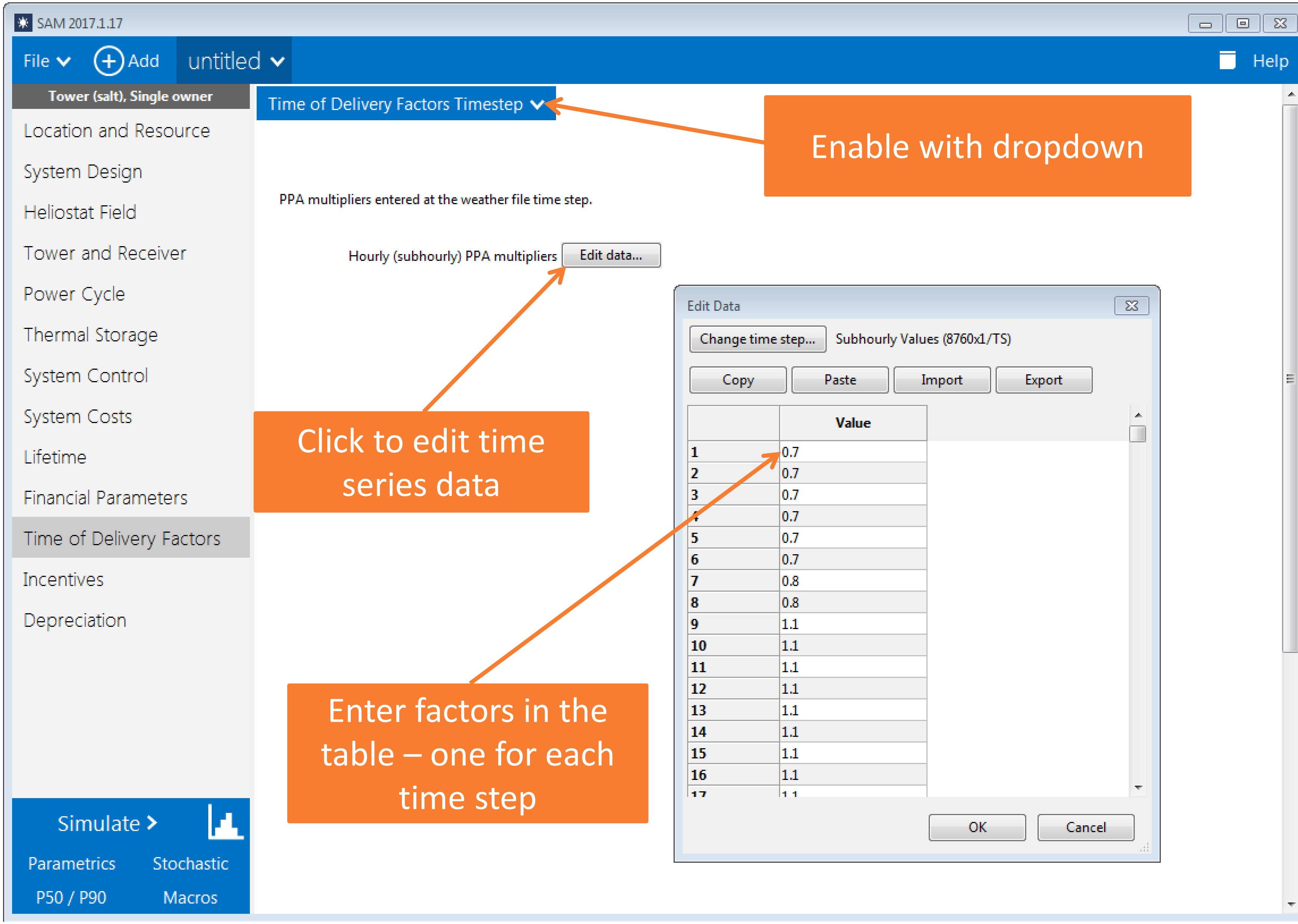


# Dispatch optimization

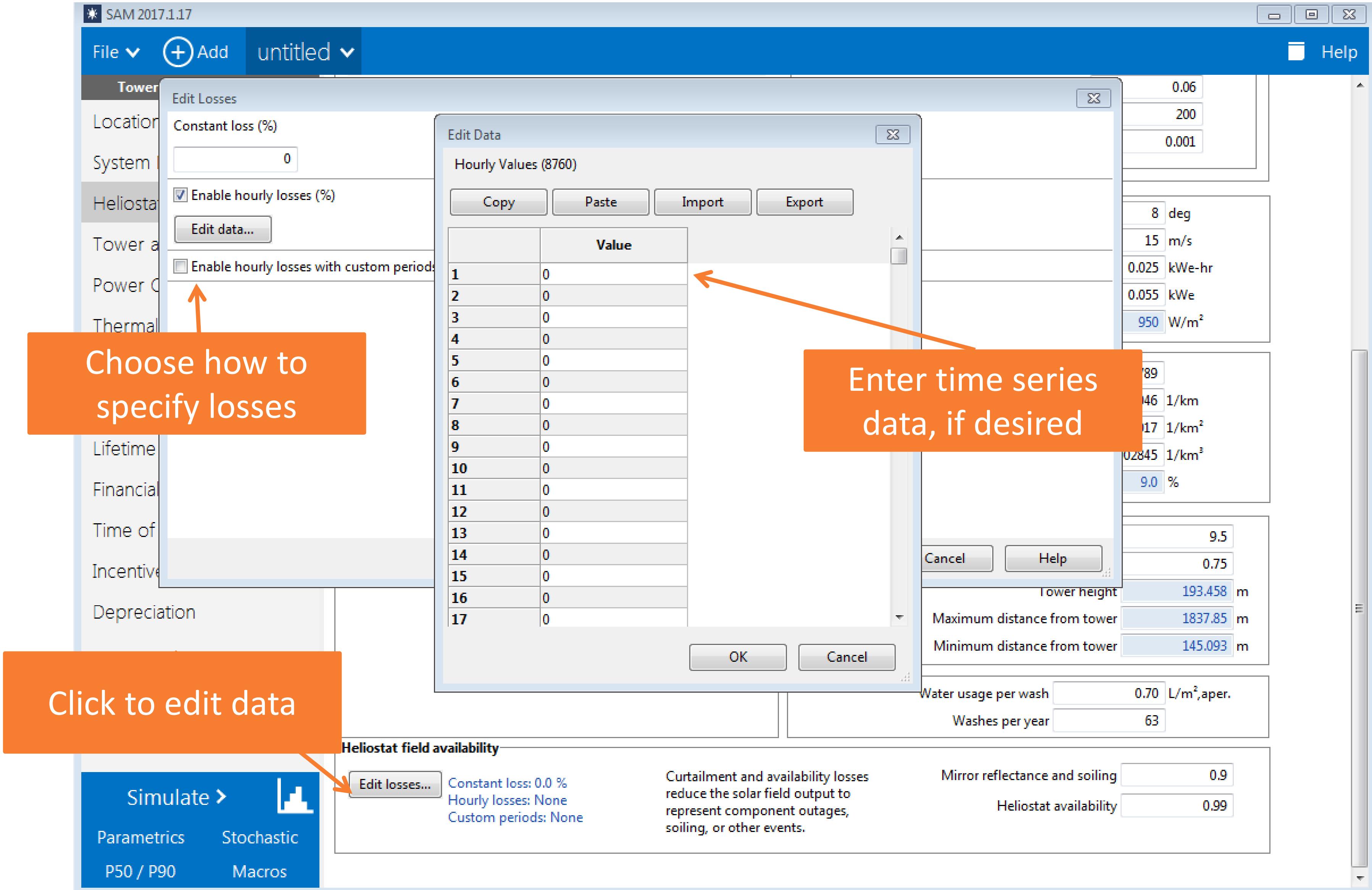
- By default, SAM generates power whenever energy is available in the storage system
- Dispatch optimization calculates the best times to generate, and determines an optimal operating profile (more on this later!)



# Hourly time-of-dispatch factors



# Improved solar field performance availability specification



# User specification of attenuation loss coefficients

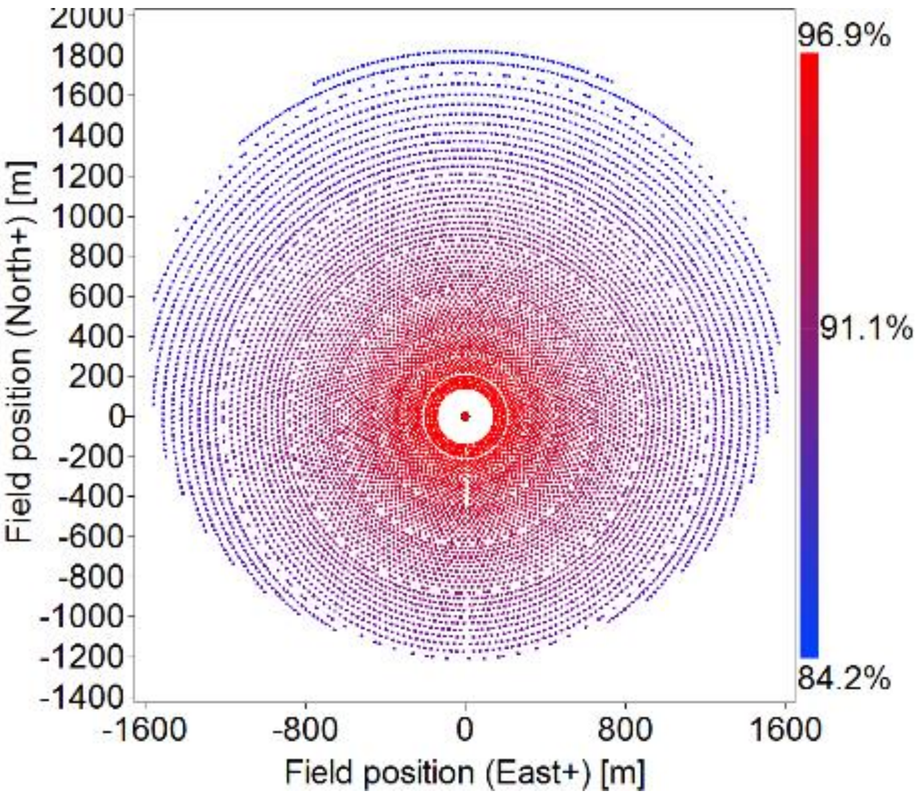
- Atmospheric attenuation models the loss due to atmospheric scattering between each heliostat and the receiver
- This varies as a function of aerosol optical depth (AOD)
- AOD is highly location-dependent and varies throughout the day and year
- SAM's defaults are for 25 km visibility in the US southwest and are likely not appropriate for MENA sites
- Polynomial is evaluated for each heliostat position to determine overall performance

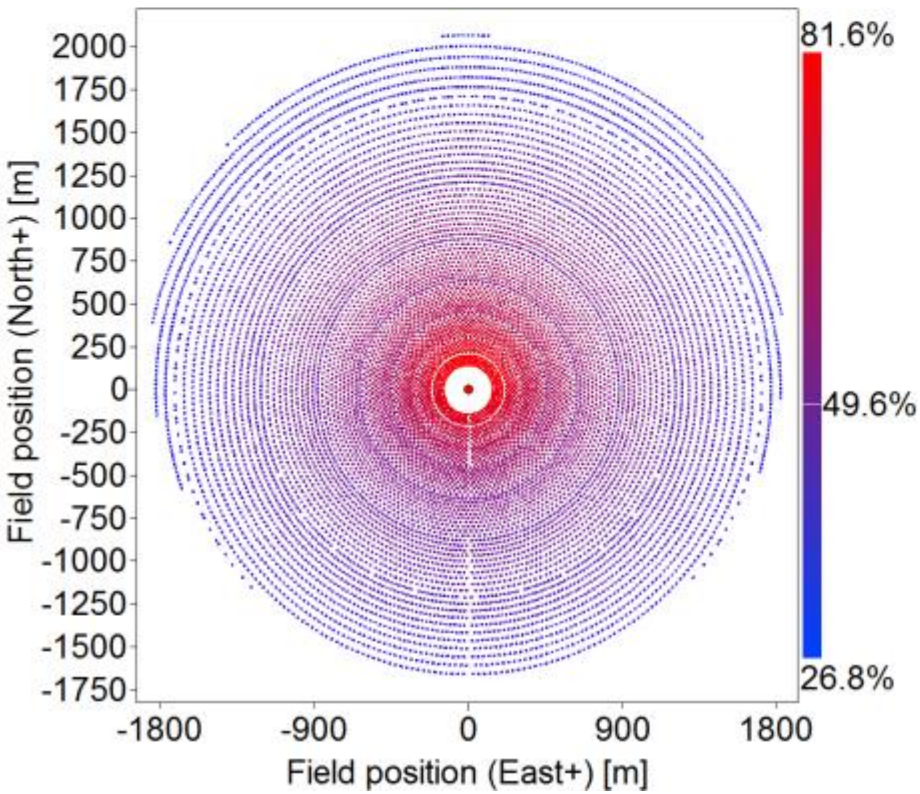
**Atmospheric Attenuation**

| | | |
|---|---|---|
| Polynomial coefficient 0 | 0.006789 | |
| Polynomial coefficient 1 | 0.1046 | 1/km |
| Polynomial coefficient 2 | -0.017 | $1/km^2$ |
| Polynomial coefficient 3 | 0.002845 | $1/km^3$ |
| Average attenuation loss | 9.0 | % |

# Attenuation loss example

| Coefficient | Clear (25km) | Hazy (5km) |
|---|---|---|
| 0 | 0.006789 | 0.01293 |
| 1 | 0.1046 | 0.2748 |
| 2 | -0.017 | -0.03394 |
| 3 | 0.002845 | 0 |
| **Avg.** | **9%** | **26%** |



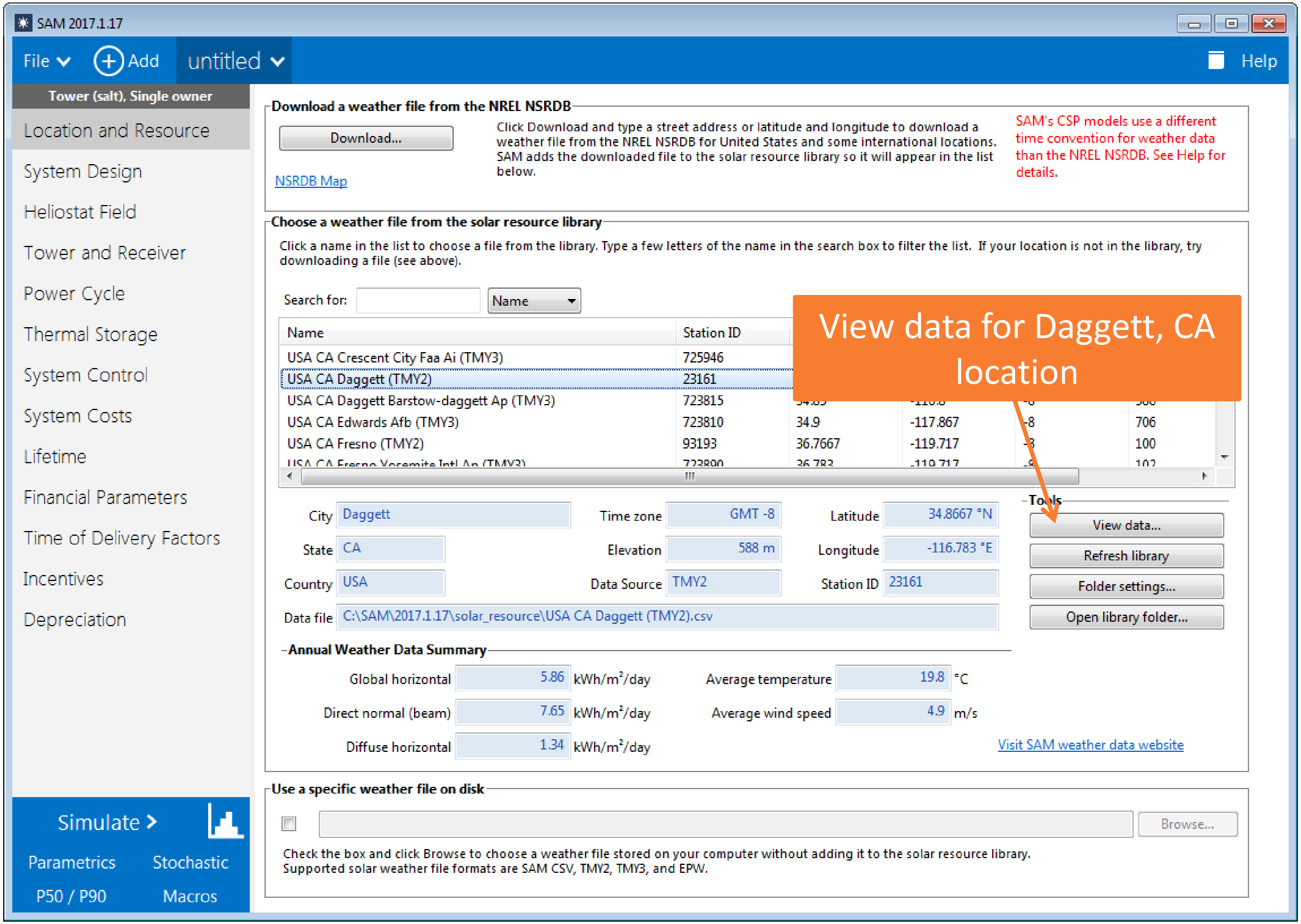



# Design-point DNI selection

# Design-point DNI selection

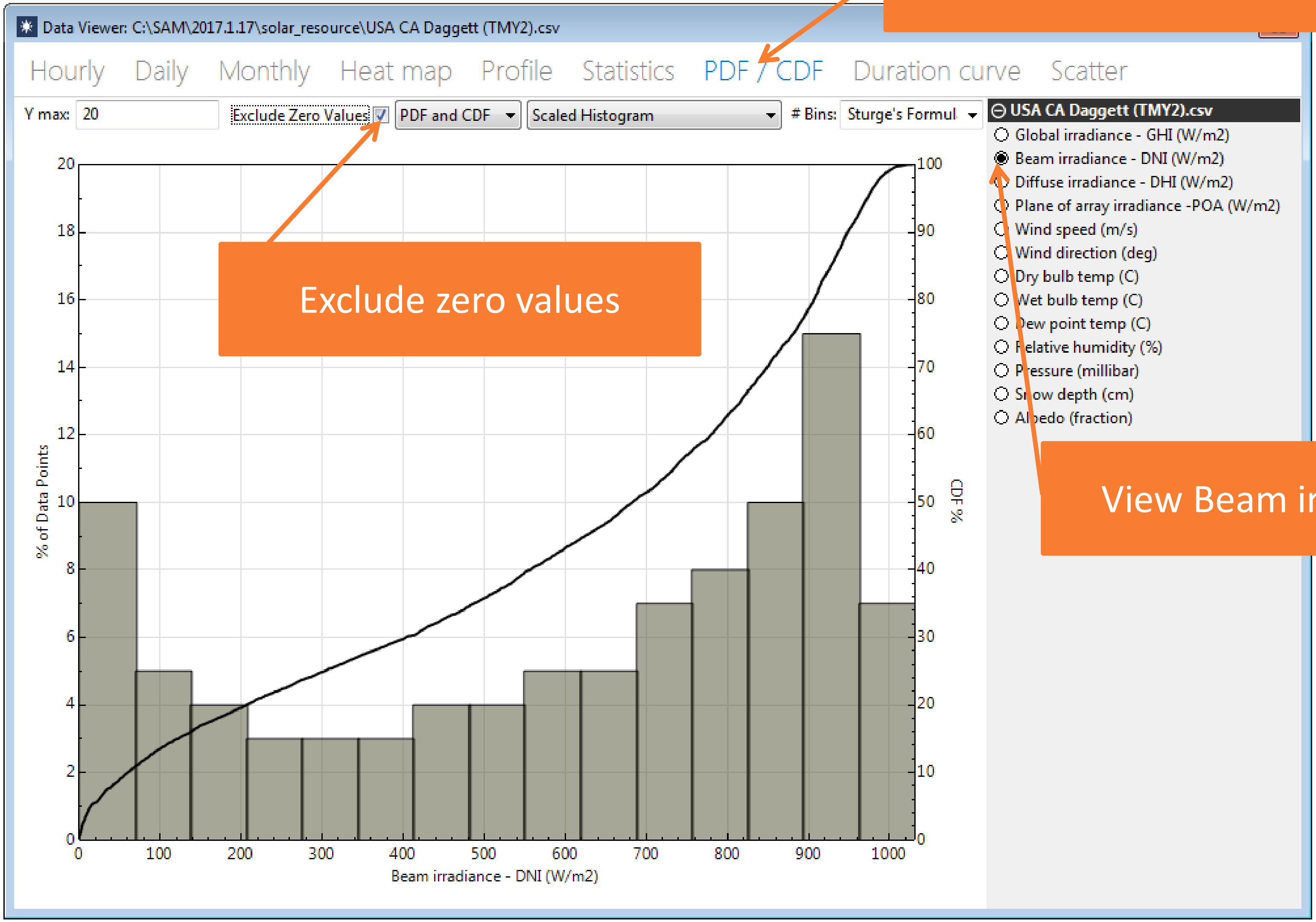
- Definition: *The direct normal irradiance (DNI) available at the design point*
- Increasing this value indicates that fewer heliostats are needed to achieve the reference condition power
- Should represent the DNI at which your plant should achieve the specified thermal rating
- SAM uses the sun position at noon on the summer solstice (June 21 north of the equator, and December 21 south of the equator)

# Selecting a design-point DNI value – default case



# Selecting a design-point DNI value – default case

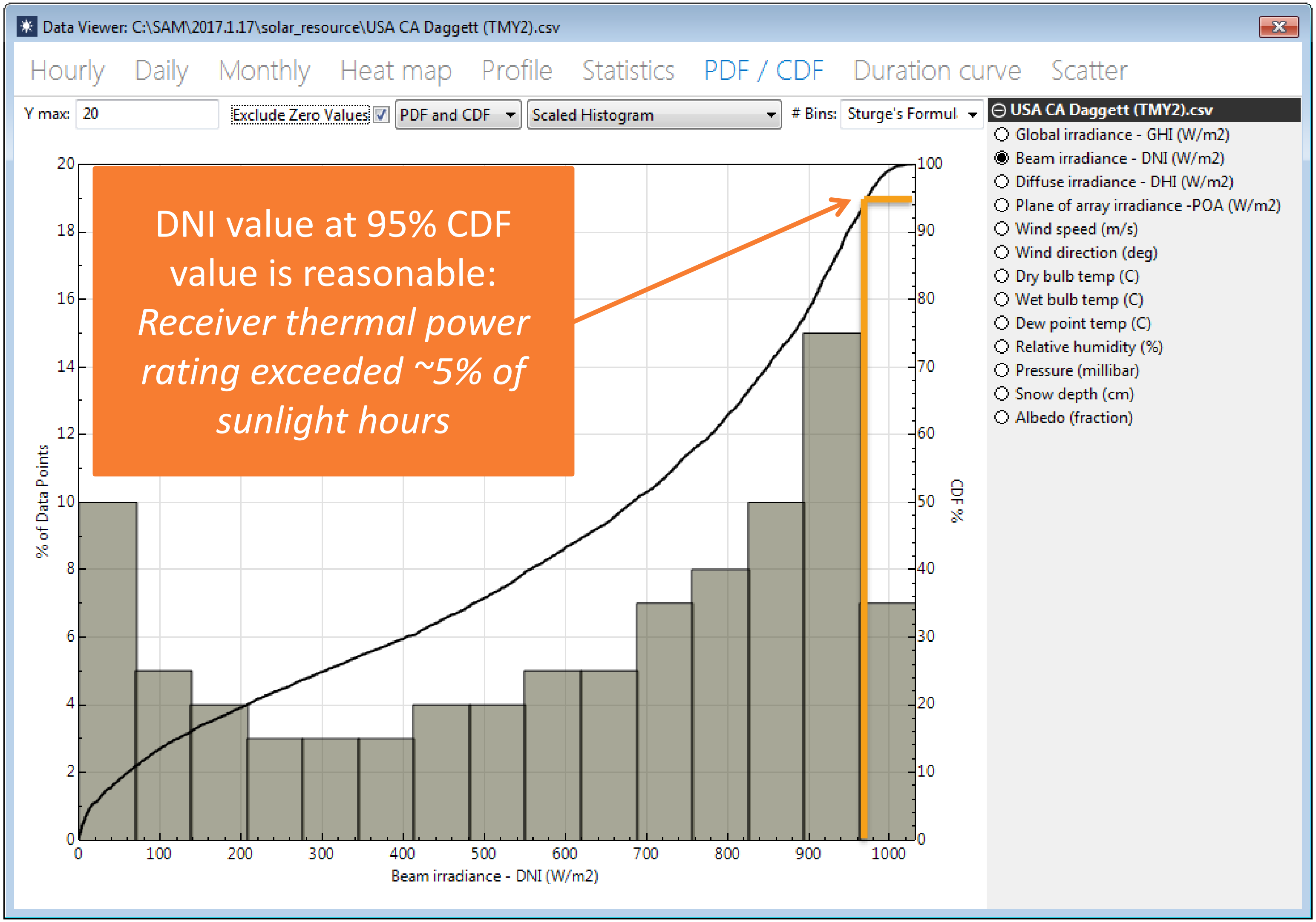
Select PDF/CDF



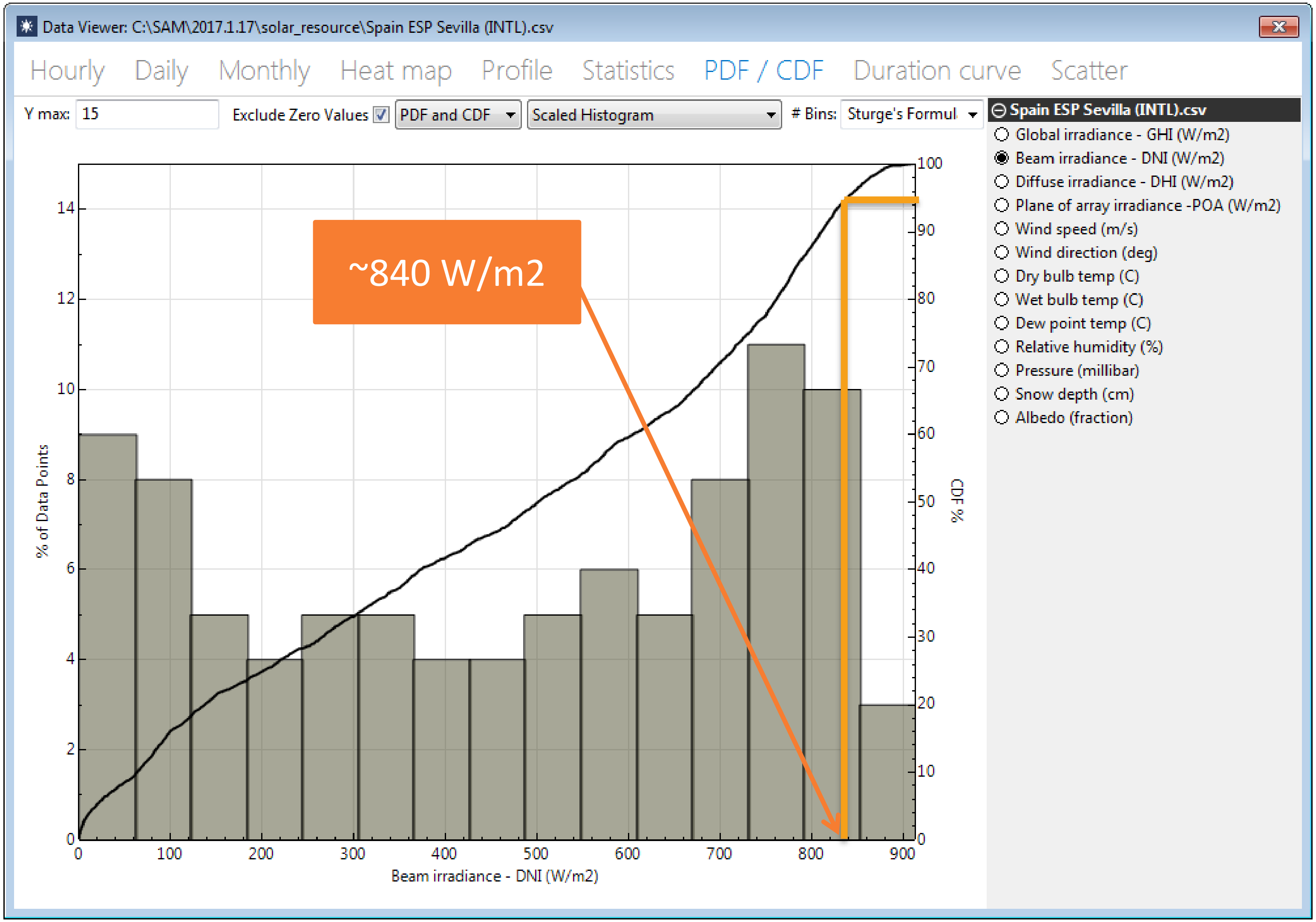

Exclude zero values

View Beam irradiance

# Selecting a design-point DNI value – default case



# Example for different climate – Sevilla, Spain

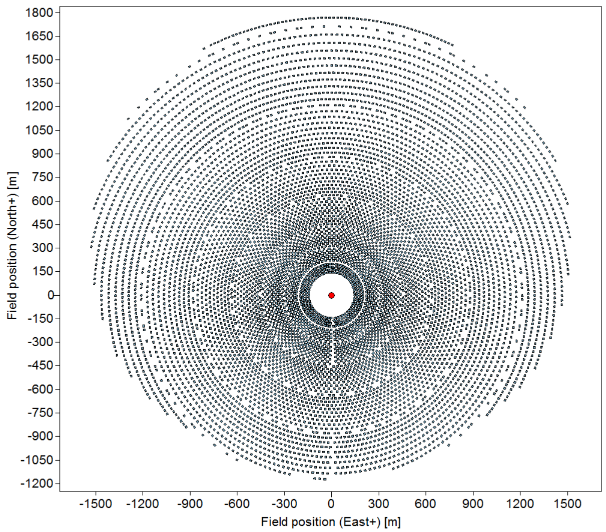


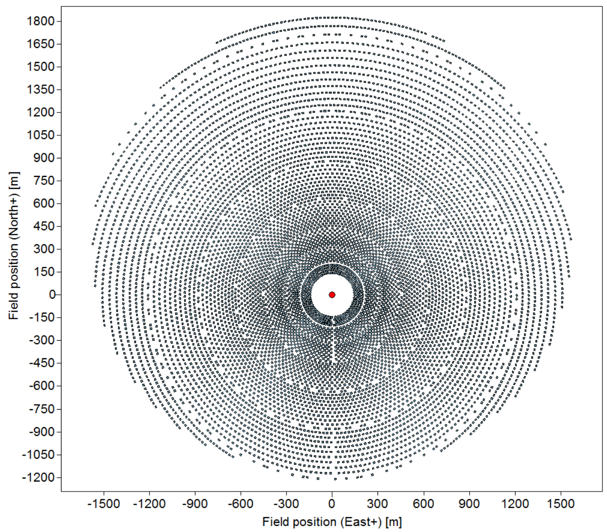
# Layout implications

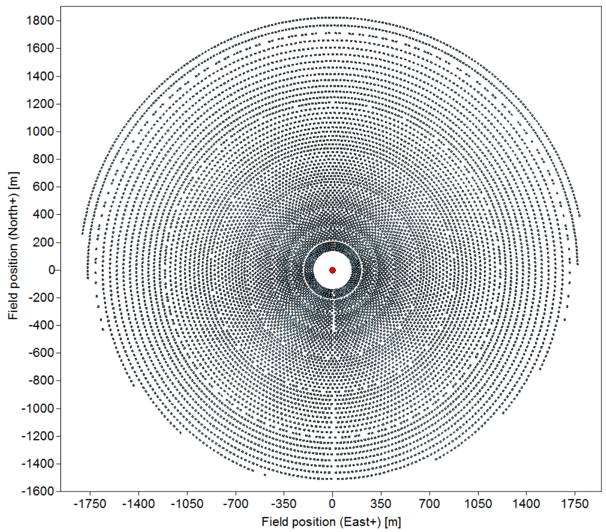
980 W/m2
8,324

950 W/m2
8,661

840 W/m2
10,163



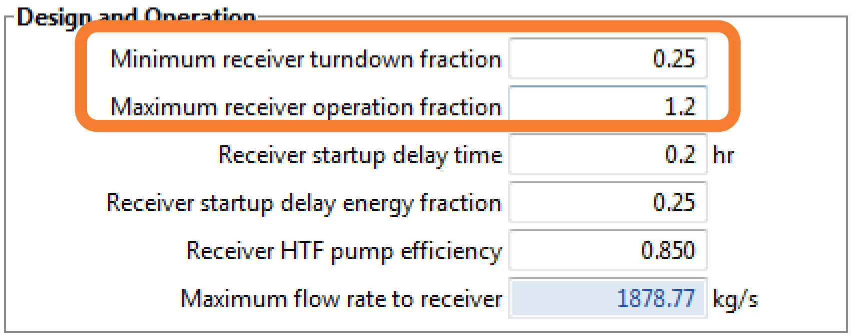




- Heliostat count does not scale linearly!

# Selecting a design-point DNI value – default case

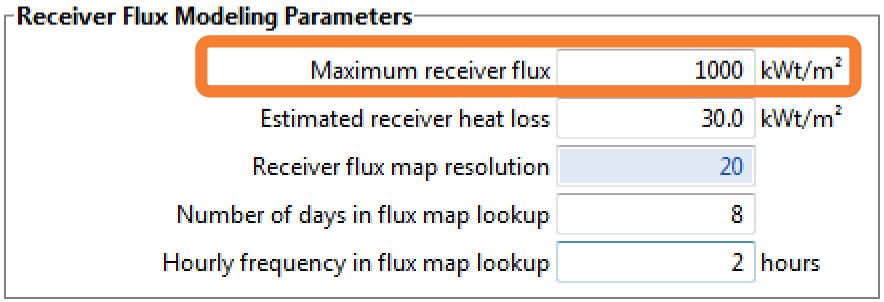
Potential pitfalls:

- DNI design point and solar multiple control separate design aspects
  - Solar multiple describes the relative thermal size of the *receiver* and *power cycle*
  - DNI design point controls the relative thermal size of the *heliostat field* and the *receiver*
- Several inputs should be aligned with the selected design point
  - Design and operation limits on the Tower and Receiver page
  - Maximum receiver flux – if design DNI is below maximum observed



**Design and Operation**

| | | |
|---|---|---|
| Minimum receiver turndown fraction | 0.25 | |
| Maximum receiver operation fraction | 1.2 | |
| Receiver startup delay time | 0.2 | hr |
| Receiver startup delay energy fraction | 0.25 | |
| Receiver HTF pump efficiency | 0.850 | |
| Maximum flow rate to receiver | 1878.77 | kg/s |



**Receiver Flux Modeling Parameters**

| | | |
|---|---|---|
| Maximum receiver flux | 1000 | $kWt/m^2$ |
| Estimated receiver heat loss | 30.0 | $kWt/m^2$ |
| Receiver flux map resolution | 20 | |
| Number of days in flux map lookup | 8 | |
| Hourly frequency in flux map lookup | 2 | hours |

# Optimizing solar field geometry

# Motivation

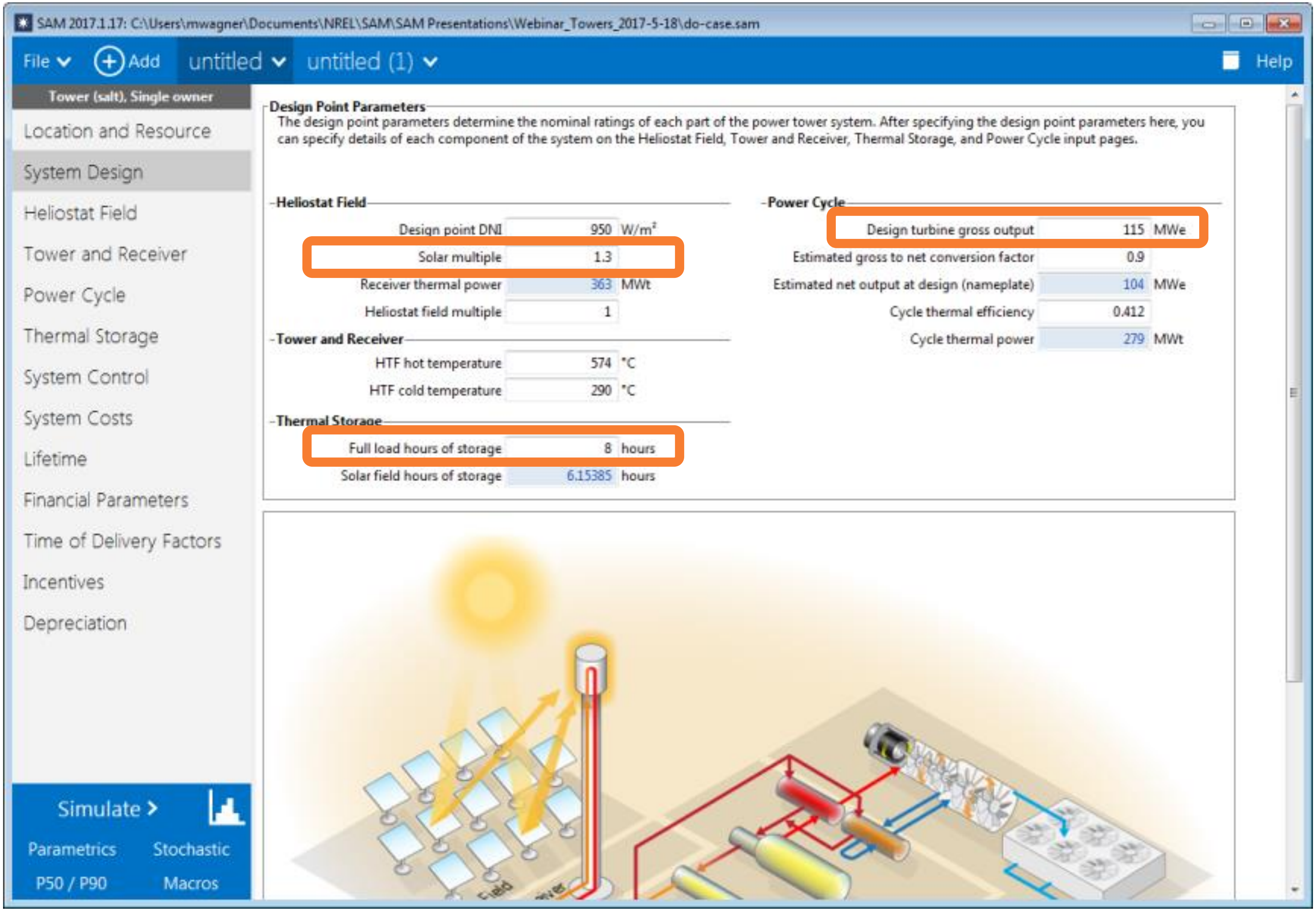
- MSPT design process is not as straightforward as other technologies
- Changes in sizing, site, or components requires new solar field design
- Many variables *could* be optimized
- SAM optimizes tower height, receiver height, receiver diameter, and heliostat positions
- SAM provides a tool to automate this process
  - Generate heliostat layout (for current receiver and tower geometry)
  - Optimize solar field geometry

# Case study

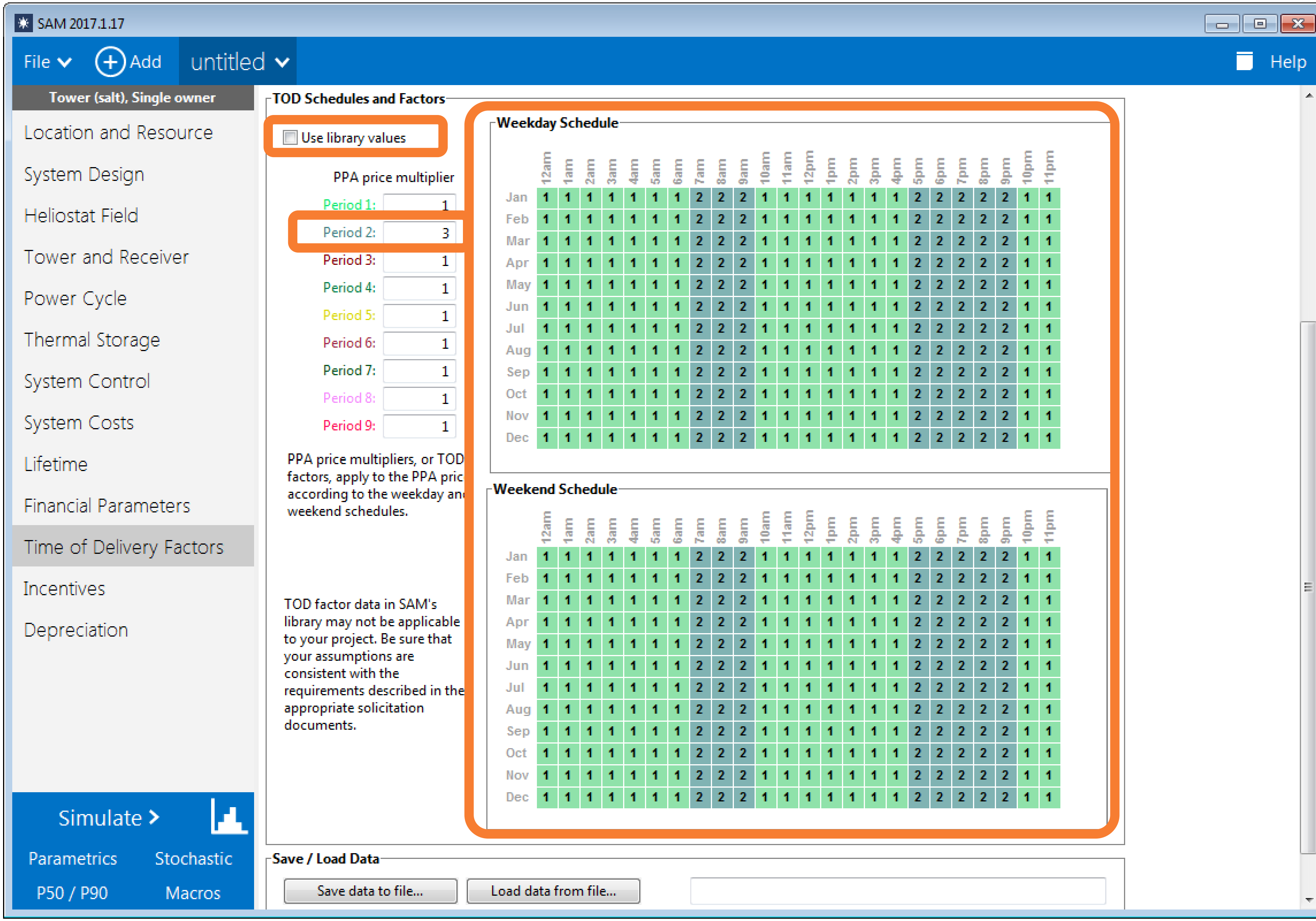
- Consider a "peaking" plant that generates during limited high-value time periods

| Parameter | Units | Value |
|---|---|---|
| Design turbine gross output | MWe | 115 |
| Solar multiple | - | 1.3 |
| Peak hours | - | 7-9; 17-21 |
| Peak multiplier | - | 3 |
| Hours of TES | Hours | 8 |

# System design settings

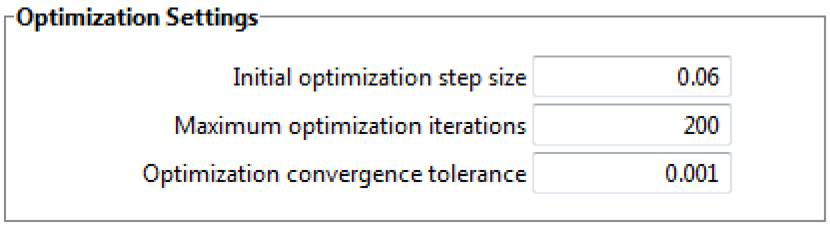


# TOD settings



# Choosing optimization settings

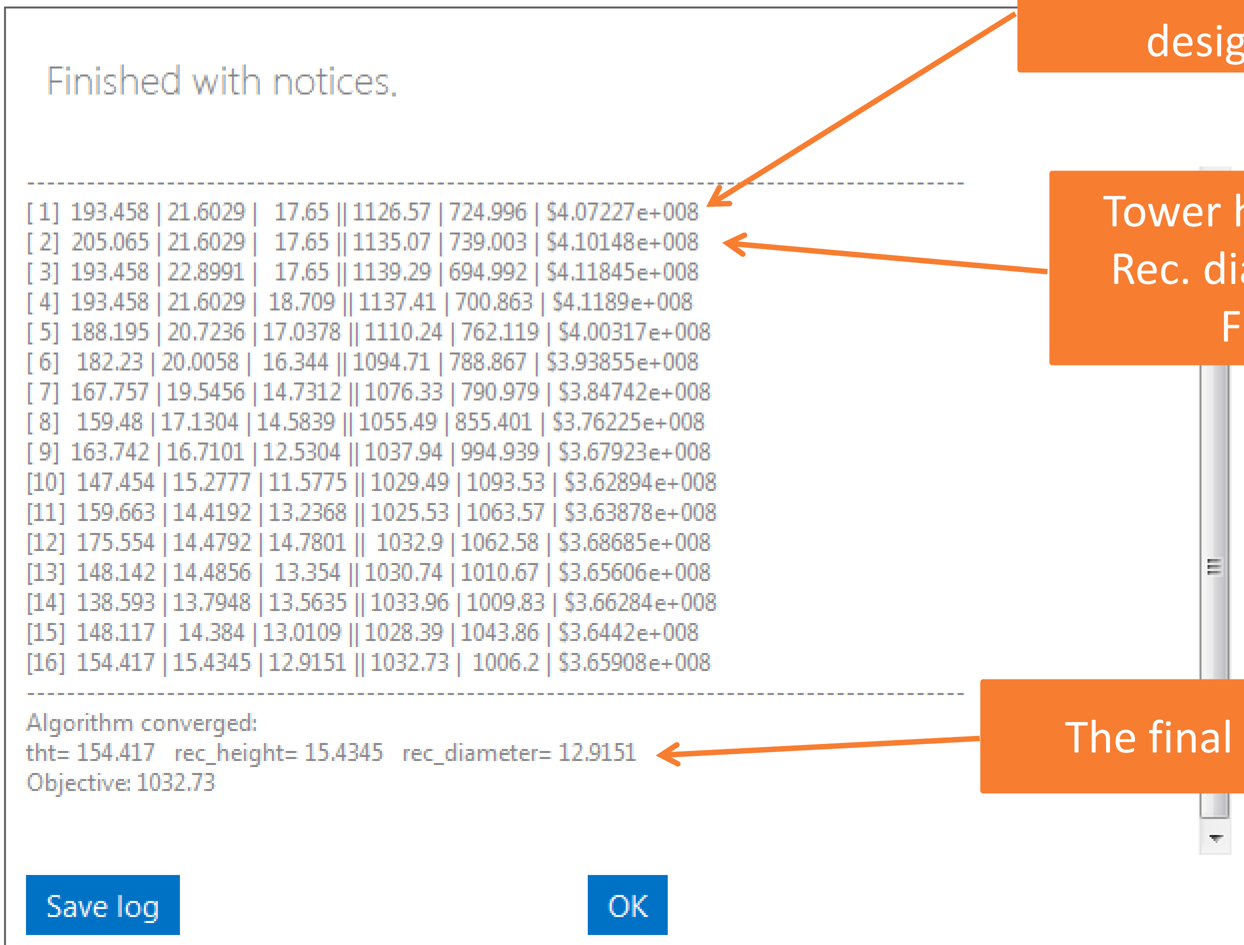
- Initial values
  - Can affect success of optimization run!
  - Choose values that are initially feasible (flux limit and thermal power requirement met)
  - Multiple runs with different initial values improve confidence of the result
- Initial step size
  - Determines how far the algorithm will jump to assess impact of changing variable values
- Maximum optimization iterations
  - Limits the number of iterations before terminating algorithm
- Optimization convergence tolerance
  - Smaller value implies more iterations before convergence
- Maximum receiver flux (Tower and Receiver page)
  - Flux on receiver evaluated at each iteration to determine feasibility



# Running the optimization

- Run time proportional to number of heliostats
- Can take some time!

Each line is an evaluation at a design configuration

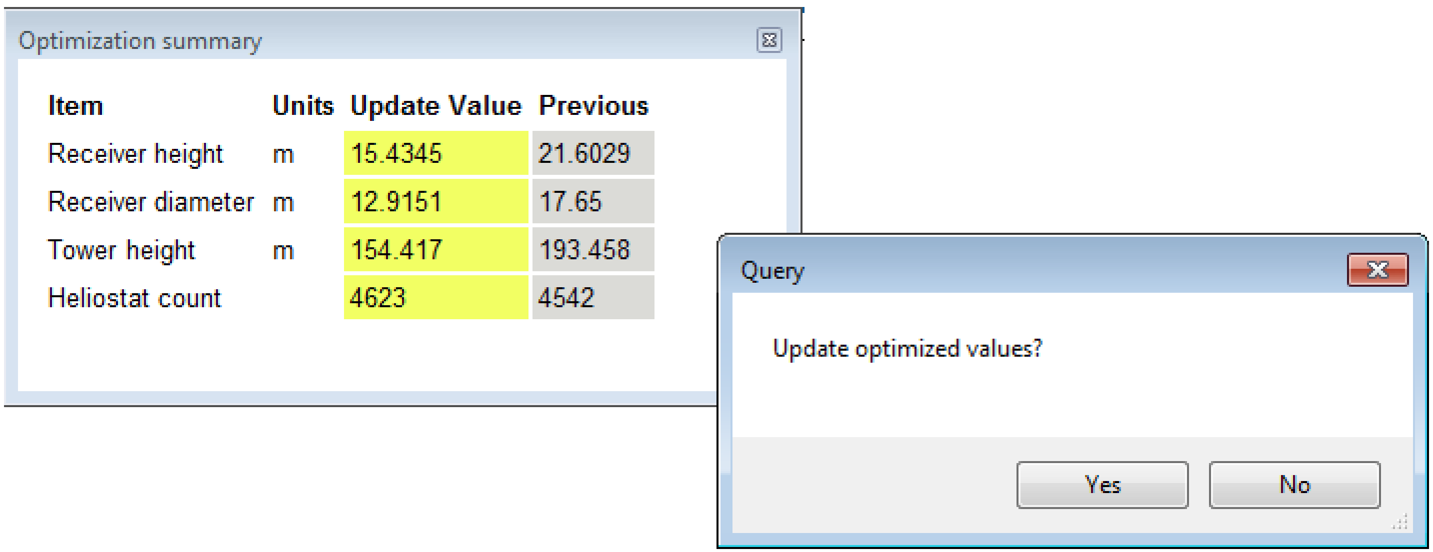



Tower height | Rec. height | Rec. diameter | Objective | Flux | Plant cost

The final result

# Accepting optimal results

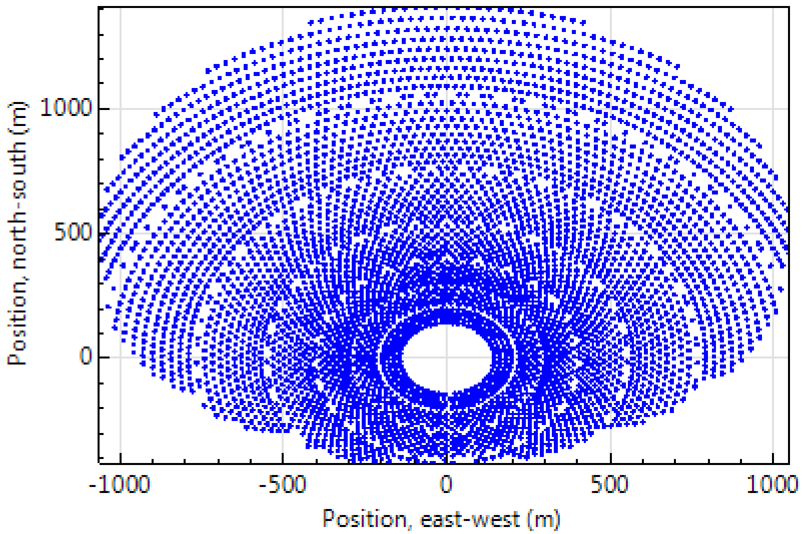
- Results are **not** automatically applied
- You can choose whether to accept the new design



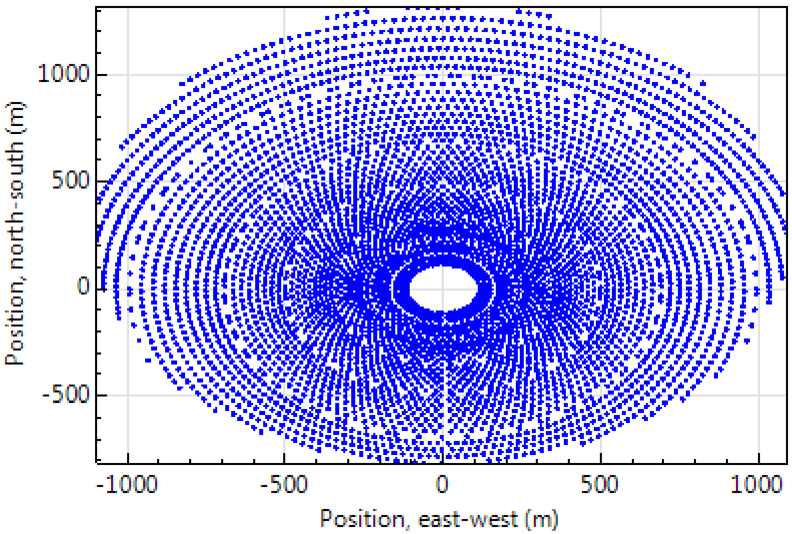
# Generating heliostat layout vs. Optimizing solar field

- Note the difference between optimizing solar field geometry vs. simply updating heliostat positions

Updated




Optimized



# After optimizing…

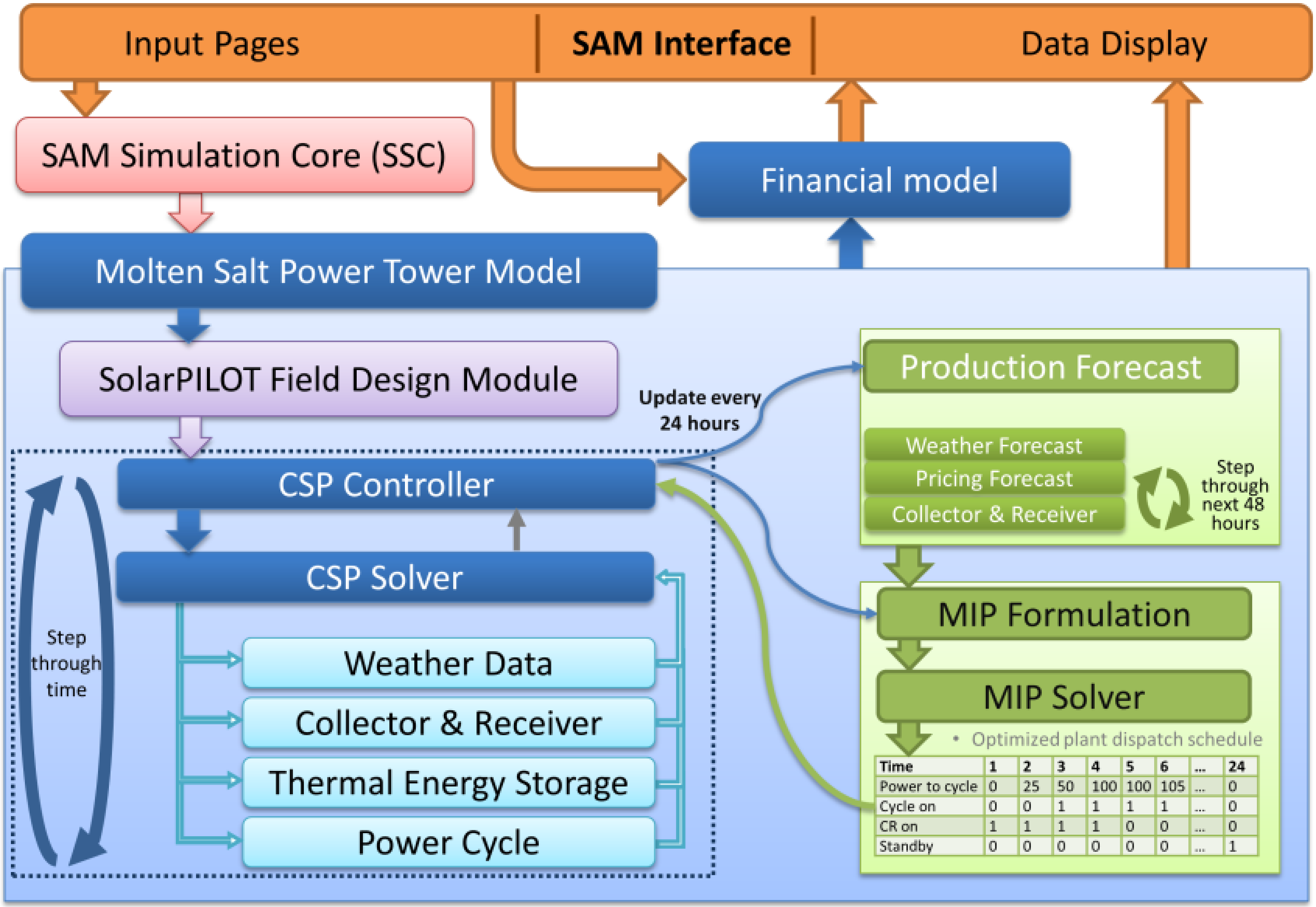
- Check different initial values of tower height, receiver dimensions
- Flux limit can constrain the solution
    - E.g., algorithm “bumps into” flux constraint, and cannot immediately determine whether violation is due to tower height or receiver dimensions
    - Resolve by temporarily relaxing flux limit, starting with different guess values, or decreasing convergence tolerance

# Optimizing dispatch

# Motivation

- Stored energy can be used over a range of possible times
- Determining when and to what extent energy should be used is not straightforward; consider:
  - Production forecast
  - Pricing forecast
  - Component performance and startup behavior
  - Day-to-day operations
- Heuristic approach uses simple rules to decide when to run the cycle
  - Maximizes energy production
  - Operates when energy in TES exceeds minimum needed to run turbine
  - Exhausts TES before shutting down
  - Does not anticipate future use
- Optimized dispatch seeks a revenue-maximizing, cost-minimizing operating profile for both the solar field and power cycle

# How does it work?




| Time | 1 | 2 | 3 | 4 | 5 | 6 | ... | 24 |
|---|---|---|---|---|---|---|---|---|
| Power to cycle | 0 | 25 | 50 | 100 | 100 | 105 | ... | 0 |
| Cycle on | 0 | 0 | 1 | 1 | 1 | 1 | ... | 0 |
| CR on | 1 | 1 | 1 | 1 | 0 | 0 | ... | 0 |
| Standby | 0 | 0 | 0 | 0 | 0 | 0 | ... | 1 |

# Dispatch optimization settings

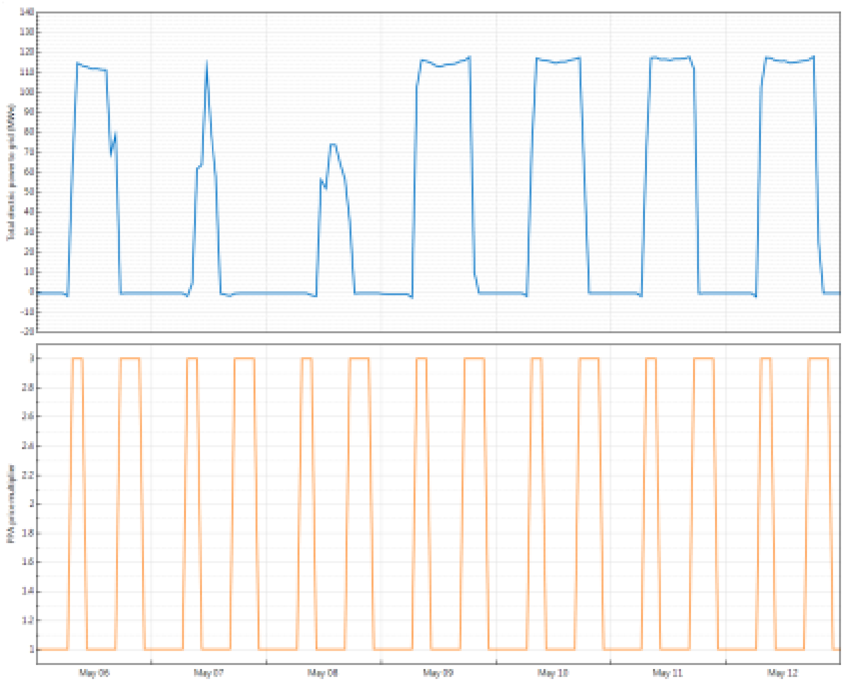
- Time horizon for dispatch optimization
  - Number of future hours considered for each optimization run
- Frequency for dispatch optimization
  - How often is dispatch re-optimized? (Daily recommended)
- Startup cost penalties
  - Cost penalty applied when startup occurs (not included in financial model!)
- Objective function time weighting exponent
  - Decisions at time *t* are discounted at the specified rate; e.g., revenue in time t=30 is $0.99^{30} \approx 0.74$ times that in t=0
- Solver settings
  - Limit number of iterations, optimality gap, or total solver time (expert)
- Max net power to the grid
  - When optimizing, control gross generation to not exceed a net power output limit

**Dispatch Optimization**

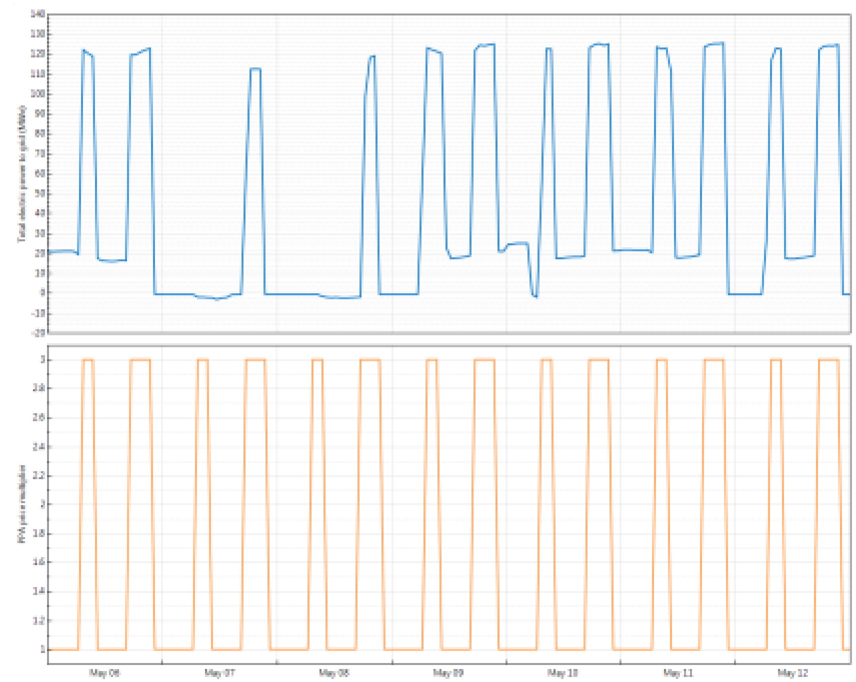
| | | | | | |
|---|---|---|---|---|---|
| Enable dispatch optimization | ☑ | | Objective function time weighting exponent | 0.99 | |
| Time horizon for dispatch optimization | 48 | hour | Maximum branch and bound iterations | 35000 | |
| Frequency for dispatch reoptimization | 24 | hour | Solution optimality gap tolerance | 0.001 | |
| Cycle startup cost penalty | 10000 | $/start | Optimization solver timeout limit | 5 | sec |
| Receiver startup cost penalty | 950 | $/start | Max. net power to the grid | 1e+038 | MWe |
| Power generation ramping penalty | 0.1 | $/ΔkWe | Max. net power to the grid (incl. availability) | 9.6e+037 | MWe |

# Comparison of performance

## Heuristic



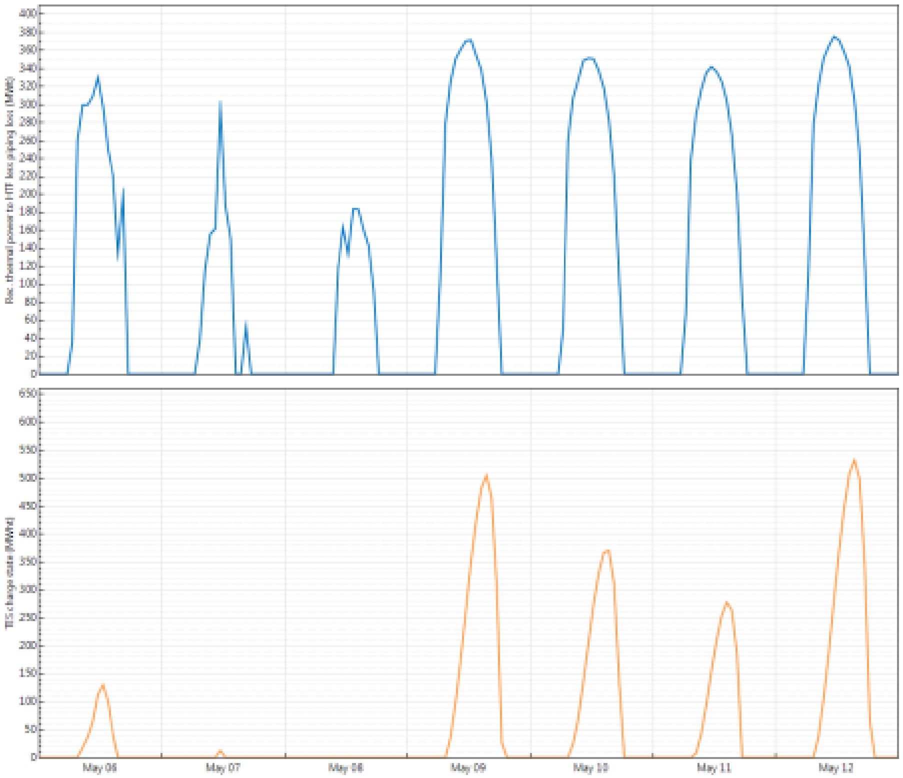
## Optimized



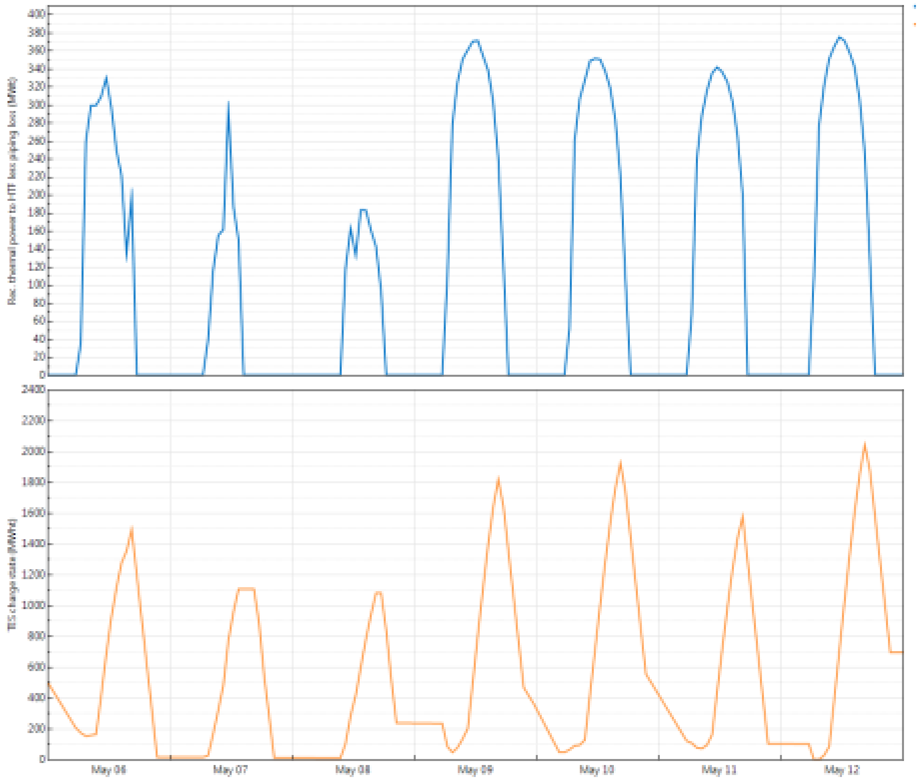
| Metric | Heuristic | Optimized |
|---|---|---|
| **Annual energy (year 1)** | 301,607,488 kWh | 289,253,696 kWh |
| **Capacity factor (year 1)** | 33.30% | 31.90% |
| **PPA price (year 1)** | 9.59 ¢/kWh | 5.96 ¢/kWh |
| **Levelized COE (real)** | 11.95 ¢/kWh | 12.44 ¢/kWh |

# TES charge state management

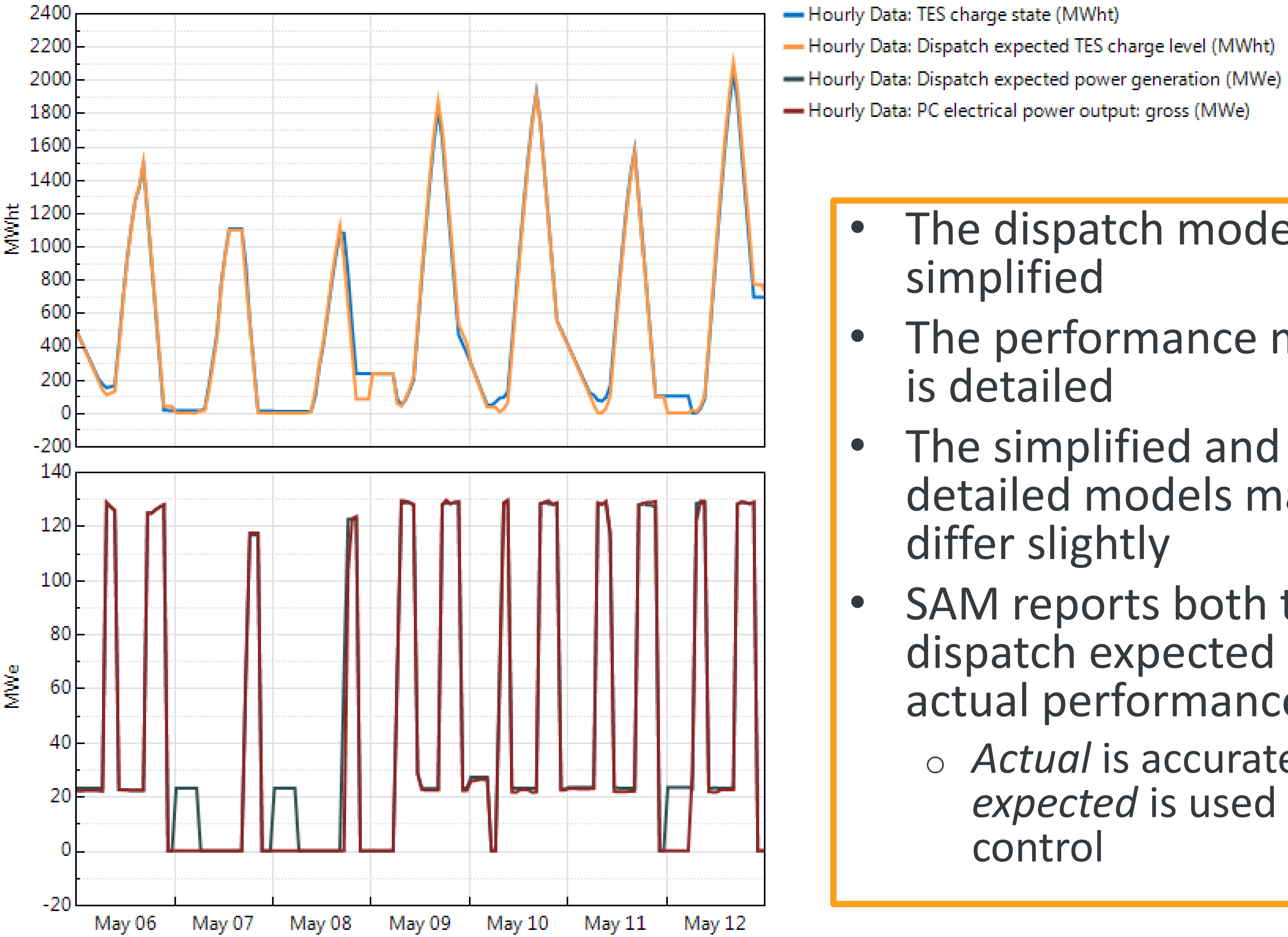
Heuristic




Optimized



# Understanding the dispatch projection vs. actuals




- The dispatch model is simplified
- The performance model is detailed
- The simplified and detailed models may differ slightly
- SAM reports both the dispatch expected and actual performance:
    - *Actual* is accurate, *expected* is used for control

# Understanding the simulation log

- If the solver cannot identify a solution for a given day, it reports the error. Each error corresponds to a single day, not the entire simulation!
  - Failed optimization reverts to heuristic dispatch
- A complete log of the optimizer results is shown on the **Notices** tab
- If a large proportion of results are suboptimal or failed, consider modifying solver settings

Finished with notices.

```
Time 1 - 49: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
Time 721 - 769: Dispatch optimization failed: Unbounded problem.
Time 1201 - 1249: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
Time 1345 - 1393: Dispatch optimization failed: Unbounded problem.
Time 2545 - 2593: Dispatch optimization failed: Unbounded problem.
Time 3385 - 3433: Dispatch optimization failed: Unbounded problem.
Time 3841 - 3889: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
Time 4009 - 4057: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
Time 5329 - 5377: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
Time 7633 - 7681: Dispatch optimization failed: Unbounded problem.
Time 8209 - 8257: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
Time 8305 - 8353: Dispatch optimization failed: Unbounded problem.
Time 8521 - 8569: Dispatch optimization failed: Iteration or time limit reached before identifying a solution.
```

Save log

OK

```
Optimizing thermal energy dispatch profile for time window 1321 - 1345
Time 1321 - 1369: Optimal solution identified.
Optimizing thermal energy dispatch profile for time window 1345 - 1369
... Unbounded dispatch optimization problem. Retrying with modified problem scaling.
... Unbounded dispatch optimization problem. Retrying with modified problem scaling.
... Unbounded dispatch optimization problem. Retrying with modified problem scaling.
... Unbounded dispatch optimization problem. Retrying with modified problem scaling.
Optimizing thermal energy dispatch profile for time window 1369 - 1393
Time 1369 - 1417: Optimal solution identified.
Optimizing thermal energy dispatch profile for time window 1393 - 1417
Time 1393 - 1441: Suboptimal solution identified.
Optimizing thermal energy dispatch profile for time window 1417 - 1441
Time 1417 - 1465: Optimal solution identified.
Optimizing thermal energy dispatch profile for time window 1441 - 1465
... Unbounded dispatch optimization problem. Retrying with modified problem scaling.
Time 1441 - 1489: Optimal solution identified.
Optimizing thermal energy dispatch profile for time window 1465 - 1489
Time 1465 - 1513: Suboptimal solution identified.
Optimizing thermal energy dispatch profile for time window 1489 - 1513
Time 1489 - 1537: Suboptimal solution identified.
Optimizing thermal energy dispatch profile for time window 1513 - 1537
Time 1513 - 1561: Suboptimal solution identified.
Optimizing thermal energy dispatch profile for time window 1537 - 1561
```

# Thank You!

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