Optical characterization of radial-staggered heliostat fields: Model validation with SolarPILOT

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Contents

1. Introduction
2. Optical characterization of power towers plants
3. Modeling with SolarPILOT
4. Plant Location and Atmospheric conditions
5. Heliostat field layout and optimization
6. Performance simulation results
7. Conclusions and outlook
1. Introduction

Heliostats in a power tower plant

Heliostats must be placed in such a way that there is minimum optical and mechanical interference from one another.

Several variables must be optimized:
- Heliostat position in the field
- Outer land boundary
- Receiver type and dimensions
- Height of the tower

Source: https://sam.nrel.gov/
1. Introduction

Power tower plant design

Location: Upington, South Africa

Plant net capacity: 100 MW_e

Thermal Energy Storage (TES): 8 hours

Solar Multiple (SM): 1.8

Heliostat field layout: Radial Staggered pattern
2. Optical characterization of power towers plants

Calculation of the reflected beam image in the target plane

Deviation due to:
- Sunshape error
- Tracking errors
- Slope errors
- Canting errors
- Structural deflection errors
- Temperature dependent errors
Two methods

Statistical approach (Monte-Carlo Ray-Tracing (MCRT))

Analytical approach (Convolution method)

Source: Pitz-paal, Robert Heliostat field design for solar thermochemical processes
2. Optical characterization of power towers plants

Statistical approach (MCRT)

Randomly chosen bundle of rays from one surface to another, with the surface irradiance proportional to the number of rays causing impact.

Replicates real photon interactions providing accurate results.

Longer processing time.

2. Optical characterization of power towers plants

Analytical approach (Convolution method)

Reflected image of a heliostat can be described by a circular normal distribution (Gaussian).

\[ F(r) = \frac{1}{2\pi \sigma^2} e^{-\frac{r^2}{2\sigma^2}} \]

\[ \sigma^2 = \sigma_{\text{sun}}^2 + \sigma_{\text{beam quality}}^2 + \sigma_{\text{astigm}}^2 + (2 \cdot \sigma_{\text{track}})^2 \]

Lower computation time.
Only a few limited shapes of the reflected image can be modelled.


single mirror, incident angle 37.6° (left: HFLCAL, right: ray tracing)
2. Optical characterization of power towers plants

Examples of codes using these methods

Statistical approach (MCRT)

• SolTrace
• MIRVAL
• HELIOS
• STRAL
• Tonatiuh

Analytical approach (Convolution method)

• UHC -RCELL Suite
• DELSOL3*

*truncated Hermite function expansion to describe the shape of the reflected image in two dimensions.

• HFLCAL

A new approach to integrate both MCRT and the analytical methods where heliostat layouts can be generated quickly while using ray-tracing techniques is highly desirable.
3. Modeling with SolarPILOT

**Solar Power tower Integrated Layout and Optimization Tool (SolarPILOT)**

Integrates analytical and MCRT approach.

Generate and optimize heliostat field layouts.

Conducting a parametric study with different heliostat templates.

A user friendly graphical user interface (GUI).

3. Modeling with SolarPILOT

SolarPILOT model description - Background

Hermite function is applied to individual heliostats.

Different from the conventional approach of DELSOL3.

DELSOL3 calculates the performance at a set of field points.

Assumption: Each field point represents the average performance in a surrounding zone of heliostats.

Source: B. Kistler, A user’s manual for DELSOL3: A computer code for calculating the optical performance and optimal system design for solar thermal central receiver plants
3. Modeling with SolarPILOT

SolarPILOT model description - Modification

New method - dynamic heliostat grouping to calculate the computationally expensive interception efficiency.

Approximating the annual yield of a power tower using a subset of time steps over a year (instead of an annual simulation).

Land areas can be specified to be included or excluded from the layout.

4. Plant location and Atmospheric conditions

Location, Sunshape, Insolation and Atmospheric attenuation

Latitude (°N): -28.433

Sunshape: Limb darkened Sun - Assumption

Insolation model: Weather data

Atmospheric attenuation model: DELSOL3 Clear day
Visibility 5 km - Assumption

Limbus: Limbus in Latin - meaning edge

Source: Brocken Inaglory - Own work, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=19842075
## System Design:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value/Description</th>
<th>Variable</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliostat total surface area (m²)</td>
<td>115.56</td>
<td>Design point DNI (W/m²)</td>
<td>950</td>
</tr>
<tr>
<td>Total surface slope error (mrad)</td>
<td>2.6</td>
<td>Layout method (-)</td>
<td>Radial Staggered</td>
</tr>
<tr>
<td>Total tracking/pointing error (mrad)</td>
<td>0.63</td>
<td>Radial spacing method (-)</td>
<td>Blocking eliminated</td>
</tr>
<tr>
<td>Receiver type (-)</td>
<td>External</td>
<td>Number of days simulated (-)</td>
<td>12</td>
</tr>
<tr>
<td>Receiver thermal power (MWt)</td>
<td>502</td>
<td>Simulation hour frequency (-)</td>
<td>1</td>
</tr>
<tr>
<td>Allowable peak flux (kW/m²)</td>
<td>1100</td>
<td>Sun location at design point (-)</td>
<td>Spring equinox</td>
</tr>
<tr>
<td>Receiver absorber area (m²)</td>
<td>869.84</td>
<td>Heliosat cost per Unit area ($/m²)</td>
<td>177</td>
</tr>
</tbody>
</table>
Response Surface Optimization algorithm calculates the Solar field design power:

\[
\dot{Q}_{sf,des} = \dot{Q}_{inc} - \dot{Q}_{h}^\alpha - \dot{Q}_{ht} - \dot{Q}_{pipe}
\]

- Thermal power incident on the receiver
- Convective and radiative heat losses
- Piping heat losses

Objective: Lowest LCOE values

Different values for the height of the tower, the receiver dimensions and heliostat positions around the receiver explored.
5. Heliostat field layout and optimization

Sun position: Solar Noon, Spring Equinox

- 7965 heliostats
- 115.56 m² heliostat
- 927 113 m² reflective area
- 212.9 m receiver optical height
## 6. Performance simulation and optimization

### Results – Model and SolarPILOT

<table>
<thead>
<tr>
<th>Result (Solar Noon, Spring Equinox)</th>
<th>Model</th>
<th>SolarPILOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosine efficiency</td>
<td>79.47 %</td>
<td>79.90 %</td>
</tr>
<tr>
<td>Blocking efficiency</td>
<td>99.07 %</td>
<td>99.40 %</td>
</tr>
<tr>
<td>Atmospheric attenuation efficiency</td>
<td>91.93 %</td>
<td>91.90 %</td>
</tr>
<tr>
<td>Heliostat reflection</td>
<td>90.25 %</td>
<td>90.25 %</td>
</tr>
<tr>
<td>Interception efficiency</td>
<td>97.53 %</td>
<td>96.10 %</td>
</tr>
<tr>
<td>Solar field efficiency</td>
<td>63.702 %</td>
<td>63.302 %</td>
</tr>
</tbody>
</table>
7. Conclusion and Outlook

Importance of Optical characterization

- Important role in Heliostat cost reduction
- Optical performance with three heliostats
- Heliostat cost-scaling, optical performance and annual O&M costs
- LCOE model, not $/ m²
Thank you!

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