Modeling Parabolic Trough Systems

SAM Webinar

Mike Wagner

June 18, 2014 1:00 p.m. MDT
SAM Webinar Schedule for 2014

Schedule

• **New Features in SAM 2013 and Beyond**
  - October 9, 2013: Paul Gilman

• **SAM PV Model Validation using Measured Performance Data**
  - December 11, 2013: Janine Freeman

• **Solar Resource Data 101**
  - February 12, 2014: Janine Freeman

• **Analysis of Electricity Rate Structures for Residential and Commercial Projects**
  - April 16, 2014: Paul Gilman

• **Modeling Parabolic Trough Systems**
  - June 18, 2014: Michael Wagner

• **Photovoltaic Shading Analysis**
  - August 27, 2014: Aron Dobos

Details

• All sessions last one hour and begin at 1 p.m. Mountain Time

• You must register to participate

• Registration is free, but space is limited

• More details, registration information, and recordings of past webinars on Learning page of SAM website

https://sam.nrel.gov/content/resources-learning-sam
Outline

• Overview of SAM Parabolic Trough Models

• Case study:

Molten Salt Trough w/ Dry Cooling
  o HTF selection
  o Modifying operating temperatures
  o Loop configuration and sizing
  o Power cycle design point specification
  o Optimization of design parameters
  o Optimization of TES and Solar Multiple
This webinar is most useful if you have...

- Familiarity with parabolic trough technology components and configurations
- A basic understanding of thermodynamics, heat transfer, and fluid mechanics
- Some experience using SAM
- Particular interest in technology (vs. cost/financial)
Parabolic Trough Technology

Solar Field

Heat Exchanger

Hot tank
Cold tank

Aux Boiler

Rankine Cycle

Wet Cooling System

Exhaust
Fuel in

NATIONAL RENEWABLE ENERGY LABORATORY
SAM Trough Performance Models

• **Physical**
  - Uses first-principle and semi-empirical models to calculate performance
  - Allows modification of geometrical and optical properties to predict performance in new design spaces

• **Empirical**
  - Performance based on empirical correlations from SEGS plant data
  - Most accurate for SEGS-like configurations, temperatures, & sizes
  - Much less computationally expensive than Physical model

*Today’s webinar uses the Physical Trough model*
Physical Trough sub-models

HTF distribution and transport

Collector and Receiver
Optical gain & thermal loss

Power Cycle
Steam generation
Turbine & feed-water
Heat rejection
Fossil backup

Thermal Storage
Storage tanks
Heat exchanger (indirect)
Inputs in SAM

The performance model input pages are where you define the system’s design parameters.

The Costs, Financing and Incentives pages determine the renewable energy system’s cost ($).
SAM Trough Demo

Molten Salt Trough with Dry Cooling
What’s interesting about molten salt?

- Higher operating temperature than oil HTF’s
- Gain in power cycle conversion efficiency
- Lower cost than oil
- More energy-dense thermal storage
- “Direct” thermal storage
- Substantially different thermal properties
- Higher freezing temperature
- Higher thermal loss
- More corrosive
Analysis questions

• How much economic benefit can a molten-salt-based trough provide?

• What are the system-level design issues for a MS trough?

• What thermal storage size is most cost-effective?
The modeling process in SAM

1. Configure receiver and collector components
2. Specify HTF and operating temperatures
3. Determine transport operation limits
4. Configure the loop
5. Specify power cycle design point
6. Specify thermal storage parameters
7. Update costs and financials
8. Optimize uncertain parameters
9. Optimize solar multiple and TES capacity
Receivers and Collectors

- **Receivers (HCEs)**
  - Loop thermal efficiency calculation uses the receiver *Estimated avg. heat loss*, which must be supplied by the user.
  - **Annulus gas type (1) = Air**
    - We are modeling molten salt, so hydrogen permeation is not a problem.
  - **Estimated average heat loss = [310, 590, 4518,0]**
    - These values can be calculated based on detailed collector performance models, or by running the model and inspecting the results near design-point conditions

- **Collectors (SCAs)**
  - **Configuration name = Solargenix SGX-1**
Heat Transfer Fluid Differences

- Viscosity, density, and heat capacity differ substantially
- Pressure loss higher in salt system at equivalent velocities
Solar field – Min/Max Flow Rate

• **Field HTF Fluid** = Hitec solar salt

• **Design loop outlet temp** = 550°C
  - Field inlet temperature related to boiling saturation temperature

• **Min/Max single loop flow rate**
  - Primary concern is maximum pressure drop
  - Therminol VP-1 velocity range [0.36, 4.97 m/s]
  - **Method (1)**: Manually try different loop lengths and flow rates in SAM
  - **Method (2)**: Match pressure drops by iteratively solving pipe pressure loss equations...
Calculating pressure loss in a pipe

Moody Diagram

Friction Factor

Material | ε (mm)
--- | ---
Concrete, coarse | 0.25
Concrete, new smooth | 0.025
Drawn tubing | 0.0025
Glass, Plastic, Perspex | 0.0025
Iron, cast | 0.15
Sewer, old | 3.0
Steel, mortar lined | 0.1
Steel, rusted | 0.5
Steel, structural or forged | 0.025
Water mains, old | 1.0

Transition Region

Transition Region

Friction Factor = \( \frac{2d}{\rho V^2 g} \Delta P \)

Smooth Pipe

Complete turbulence

Reynolds Number, \( Re = \frac{\rho V d}{\mu} \)
(1) Establish a reference pressure loss

- **Use Therminol-VP1 settings to calculate a reference pressure loss**
  - Use maximum Therminol velocity
  - Calculate Reynolds number
  - Look up friction factor on Moody Chart
  - Initial reference length is \( l_{ref} = 1.0 \)
  - Solve pressure loss eqn. for \( \Delta P_{ref} \)

- **We will try to set up the salt loop to match this ref. pressure constant**

\[
D = 0.066 \, m
\]
\[
V_T = 5 \, \frac{m}{s}
\]
\[
Re_T = \frac{\rho_T V_T D}{\mu_T} = 1.39e6
\]
\[
f_{fT} = 0.011
\]
\[
\Delta P_{ref} = f_{fT}(Re_T)\frac{\rho_T V_T^2 l_{ref}}{2D} = 1610 \, Pa
\]
(2) Calculate salt mass flow rate

- Use energy balance to calculate mass flow rate
  - Absorption energy balance
  - First-law balance

- Need to guess number of SCA’s!
  - (will refine with iteration)

\[ \dot{q}_{\text{loop}} = A_{\text{sca}} \eta_{\text{abs}} N_{\text{sca}} I_{bn} \]

\[ \dot{q}_{\text{loop}} = \dot{m}_s c_{ps} \Delta T_s \]

\[ \dot{m}_s = \frac{A_{\text{sca}} \eta_{\text{abs}} N_{\text{sca}} I_{bn}}{c_{ps} \Delta T_s} \]

\[ = 6.4 \frac{kg}{s} \]

\[ I_{bn} = 950 \frac{W}{m^2} \quad A_{\text{sca}} = 470.3 \, m^2 \]

\[ c_{ps} = 1520 \frac{J}{kg \, K} \quad \eta_{\text{abs}} = 0.689 \]

\[ \Delta T_s = (550 - 293) = 257 \, ^{\circ}C \]
(3) Calculate velocity and new length

- Calculate velocity for mass flow rate
  \[ V_s = \frac{\dot{m}_s}{\rho_s \pi \left( \frac{D}{2} \right)^2} = 1.02 \frac{m}{s} \]

- Calculate Reynolds number
  \[ Re_s = \frac{\rho_s V_s D}{\mu_s} = 75254 \]

- Look up friction factor
  \[ f(Re_s) = 0.0195 \]

- Solve pressure eqn. for length
  \[ l'_\text{ref} = \frac{\Delta P_{\text{ref}} 2D}{\rho_s V_s^2 f_{fs}} = 5.75 \]

- The new length is used to update the estimate of No. of SCA’s
  - Pressure highly nonlinear! Be conservative...
    \[ N'_{\text{sca}} = 46? \]
    \[ l'_{\text{ref}} = 2 \rightarrow N'_{\text{sca}} = 16 \]
(4) Finally.. Iterate to convergence on L

<table>
<thead>
<tr>
<th>Iter</th>
<th>$m_s$ kg/s</th>
<th>$V_s$ m/s</th>
<th>$Re_s$</th>
<th>$f_{fs}(Re_s)$</th>
<th>$U'$</th>
<th>$N_{sca}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.4</td>
<td>1.02</td>
<td>75254</td>
<td>0.0195</td>
<td>5.75</td>
<td>16</td>
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<tr>
<td>2</td>
<td>12.8</td>
<td>2.05</td>
<td>151247</td>
<td>0.0165</td>
<td>1.68</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>11.2</td>
<td>1.80</td>
<td>132802</td>
<td>0.017</td>
<td>2.11</td>
<td>16</td>
</tr>
</tbody>
</table>

- **Number of SCA/HCE Assemblies** = 14
- **Max HTF Flow rate** = 12.8 kg/s
- **Min HTF Flow rate** = 1.75 kg/s
Other Solar Field Settings

- **Min/Max Header Velocity** = [0.7 m/s, 1.2 m/s]
- **Freeze protection temp** = 260°C
  - Must maintain HTF above freezing temperature
- **Number of field subsections** = 8
  - Relatively large field, so increase divisions. Ultimately, a parametric simulation can be run to determine which layout is best

![Graph showing PPA price vs. Number of Field Subsections]
Power Cycle – Dry Cooling

- **Condenser type** = Air-cooled
- **Ambient temp at design** = 42°C
  - Condensing temperature is \( T_{amb} + \Delta T_{ITD} = 58°C \)
- **Rated cycle conversion efficiency**
  - Prefer detailed external model, but... not always available
  - Reference cycle – Molten Salt power tower w/ 550°C steam temperature at 41.2% gross efficiency
  - Assume 20°C salt-to-steam temperature drop
  - When in doubt, use Carnot scaling:
    - \( \eta_1 = 1 - \frac{273.15 + 58}{550 + 273.15} = 0.5977 \)
    - \( \eta_2 = 1 - \frac{273.15 + 58}{530 + 273.15} = 0.5877 \)
    - \( \eta = 0.412 \frac{\eta_2}{\eta_1} = 0.4051 \)
Power cycle – Other parameters

• **Design gross output** = 167 MWe
  o Increase design gross until the estimated nameplate capacity meets the target

• **Aux heater outlet set temp** = 550°C
  o Not used in this example, but good practice

• **Minimum required startup temp** = 360°C
  o Trade HTF temperature for lower-efficiency cycle operation
  o Optimize!
Thermal storage parameters

- Ensure **HTF** = Hitec Solar Salt
  - No intermediate HX is required
- **Tank height** = 15
  - How reasonable is the calculated tank diameter?
- **Parallel tank pairs** = 2
- **Cold tank heater set point** = 260°C
  - Match freeze protection temperature setting
- **Hot tank heater set point** = 525°C
  - Don’t allow significant decay in hot TES temperature
Costs

• This example doesn’t consider detailed cost information!
  o Minor changes to reflect updated HTF
• **Storage cost** = 30 $/kWht
• **Power plant** = 1200 $/kWe
Simulation & Results (in SAM)
Optimizing thermal storage and solar multiple

LCOE vs. Solar multiple (Par. 1)

- LCOE Real {Full load hours of TES=4}
- LCOE Real {Full load hours of TES=7}
- LCOE Real {Full load hours of TES=10}
- LCOE Real {Full load hours of TES=13}
- LCOE Real {Full load hours of TES=16}
Optimizing...

PPA vs. Solar multiple (Par. 1)

- PPA price (Full load hours of TES=4)
- PPA price (Full load hours of TES=7)
- PPA price (Full load hours of TES=10)
- PPA price (Full load hours of TES=13)
- PPA price (Full load hours of TES=16)
## Comparison: MS vs Oil trough

<table>
<thead>
<tr>
<th>Metric</th>
<th>MS Optimized</th>
<th>Value</th>
<th>Oil Trough Optimized</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Energy</td>
<td>746,036,992 kWh</td>
<td><strong>PPA price</strong></td>
<td>349,266,368 kWh</td>
<td><strong>15.30 ¢/kWh</strong></td>
</tr>
<tr>
<td>PPA price</td>
<td><strong>14.16 ¢/kWh</strong></td>
<td>LCOE Nominal</td>
<td>19.24 ¢/kWh</td>
<td>19.50%</td>
</tr>
<tr>
<td>LCOE Real</td>
<td>16.80 ¢/kWh</td>
<td>LCOE Nominal</td>
<td>19.24 ¢/kWh</td>
<td>15.55 ¢/kWh</td>
</tr>
<tr>
<td>Internal rate of return (%)</td>
<td>19.35%</td>
<td>LCOE Real</td>
<td>15.55 ¢/kWh</td>
<td>15.55 ¢/kWh</td>
</tr>
<tr>
<td>Minimum DSCR</td>
<td>1.43</td>
<td>Internal rate of return (%)</td>
<td>19.50%</td>
<td>19.50%</td>
</tr>
<tr>
<td>Net present value ($)</td>
<td>$137,266,240.00</td>
<td>Minimum DSCR</td>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>Calculated ppa escalation (%)</td>
<td>1.00%</td>
<td>Net present value ($)</td>
<td>$73,059,680.00</td>
<td></td>
</tr>
<tr>
<td>Calculated debt fraction (%)</td>
<td>50.00%</td>
<td>Calculated ppa escalation (%)</td>
<td>1.00%</td>
<td>1.00%</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>56.70%</td>
<td>Calculated debt fraction (%)</td>
<td>50.00%</td>
<td>50.00%</td>
</tr>
<tr>
<td>Gross to Net Conv. Factor</td>
<td>0.93</td>
<td>Capacity factor</td>
<td>39.90%</td>
<td></td>
</tr>
<tr>
<td>Annual Water Usage</td>
<td>141,351 m3</td>
<td>Gross to Net Conv. Factor</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Total Land Area</td>
<td>1961.13 acres</td>
<td>Annual Water Usage</td>
<td>1,317,661 m3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Land Area</td>
<td>898.08 acres</td>
<td></td>
</tr>
</tbody>
</table>