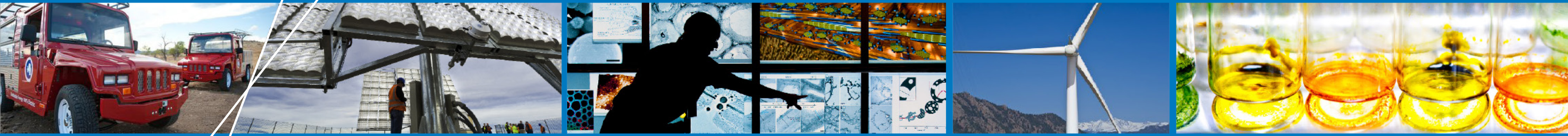
Modeling Parabolic Trough Systems



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**

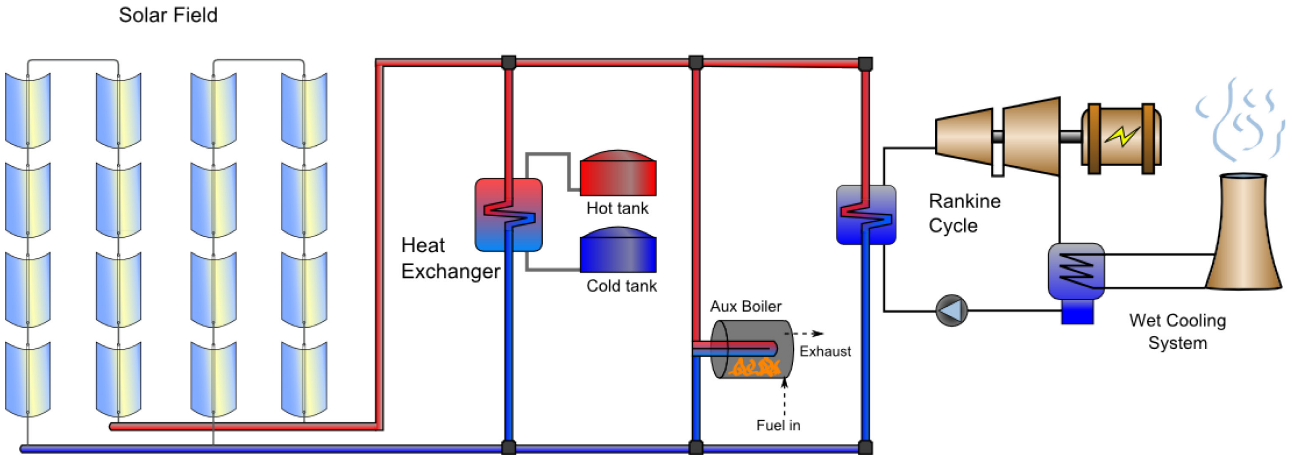
- Case study:

  Molten Salt Trough w/ Dry Cooling
  - HTF selection
  - Modifying operating temperatures
  - Loop configuration and sizing
  - Power cycle design point specification
  - Optimization of design parameters
  - 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



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

Today's webinar uses the Physical Trough model

- **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

Physical Trough sub-models

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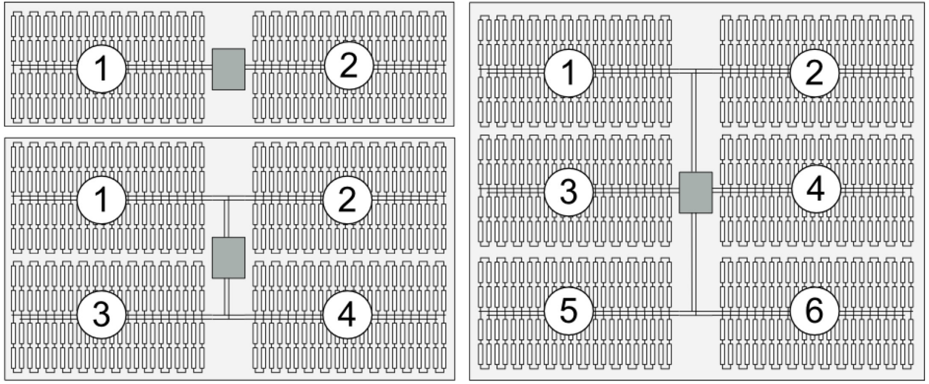
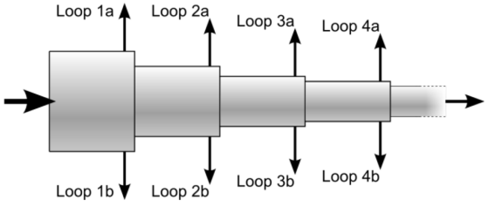
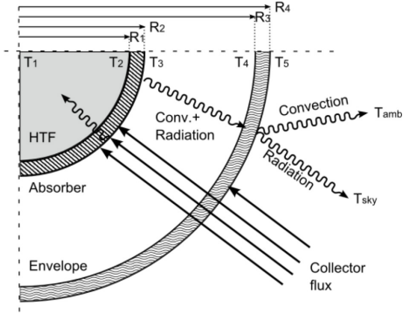


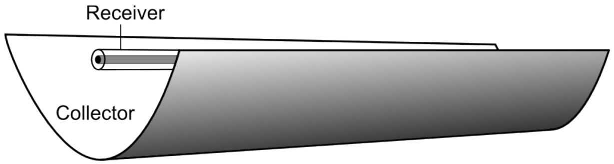


HTF distribution and transport



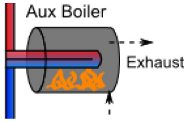
Collector and Receiver

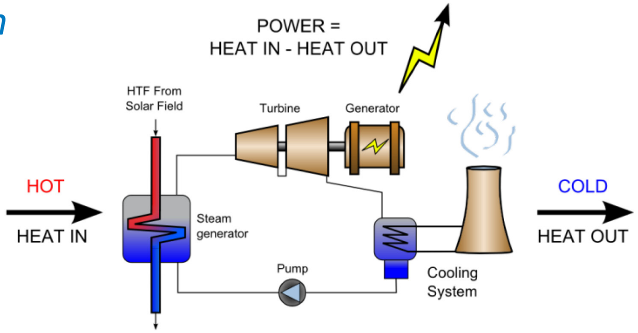
Optical gain & thermal loss



Power Cycle

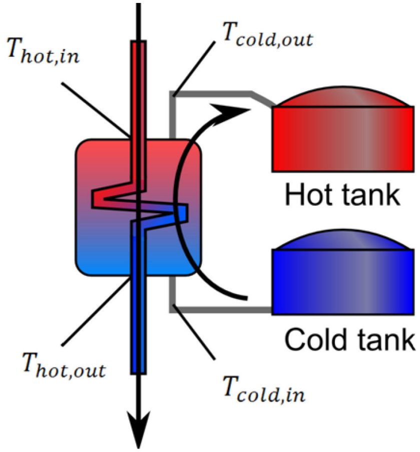
Steam generation
Turbine & feed-water
Heat rejection
Fossil backup





Thermal Storage

Storage tanks
Heat exchanger (indirect)



Inputs in SAM

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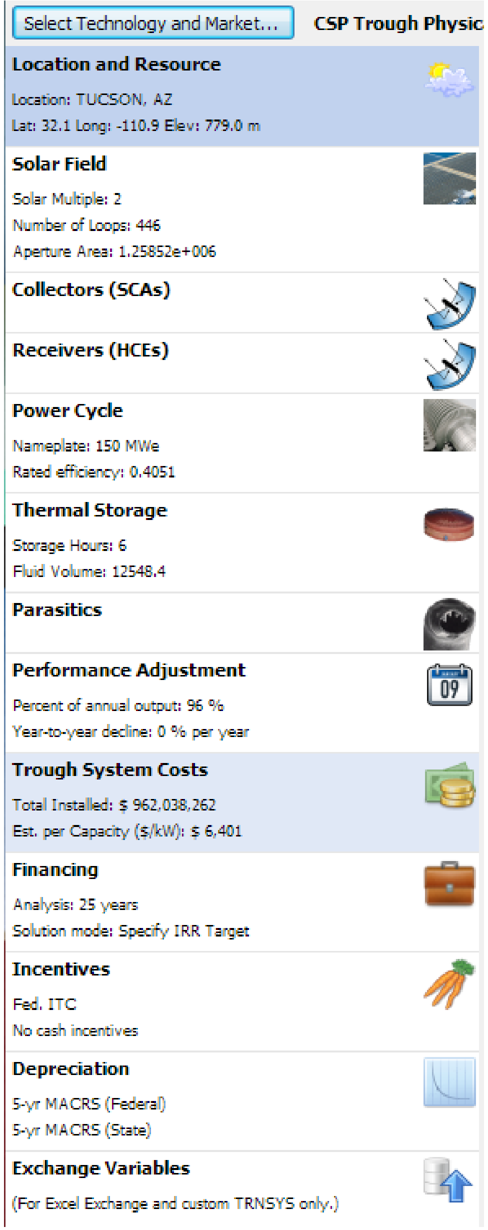


Location and Resource
Location: TUCSON, AZ
Lat: 32.1 Long: -110.9 Elev: 779.0 m

Solar Field
Solar Multiple: 2
Number of Loops: 446
Aperture Area: 1.25852e+006

Collectors (SCAs)

Receivers (HCEs)

Power Cycle
Nameplate: 150 MWe
Rated efficiency: 0.4051

Thermal Storage
Storage Hours: 6
Fluid Volume: 12548.4

Parasitics

Performance Adjustment
Percent of annual output: 96 %
Year-to-year decline: 0 % per year

Trough System Costs
Total Installed: $ 962,038,262
Est. per Capacity ($/kW): $ 6,401

Financing
Analysis: 25 years
Solution mode: Specify IRR Target

Incentives
Fed. ITC
No cash incentives

Depreciation
5-yr MACRS (Federal)
5-yr MACRS (State)

Exchange Variables
(For Excel Exchange and custom TRNSYS only.)

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

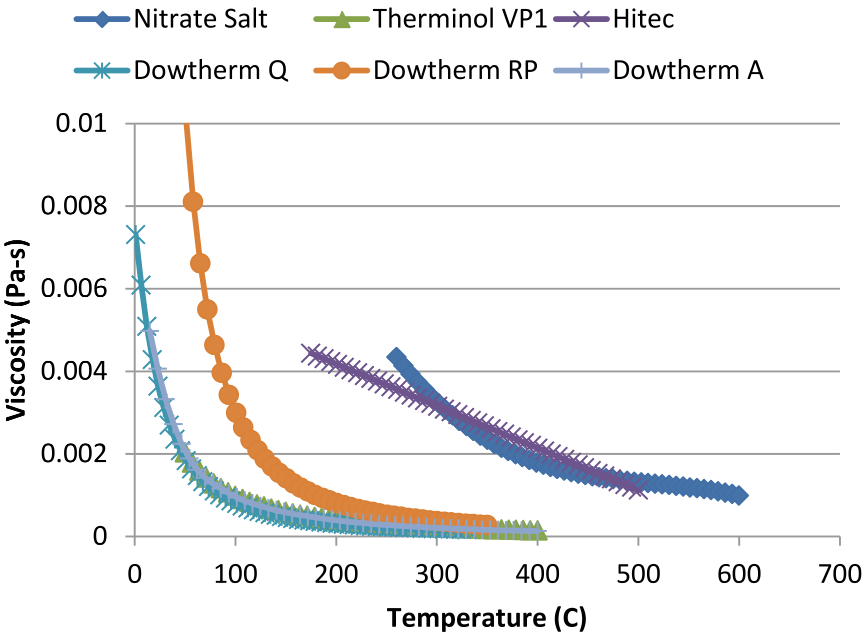
1. Configure receiver and collector components
2. Specify HTF and operating temperatures
3. Determine transport operation limits
4. Configure the loop
5. Specify power cycle design point
6. Specify thermal storage parameters
7. Update costs and financials
8. Optimize uncertain parameters
9. Optimize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

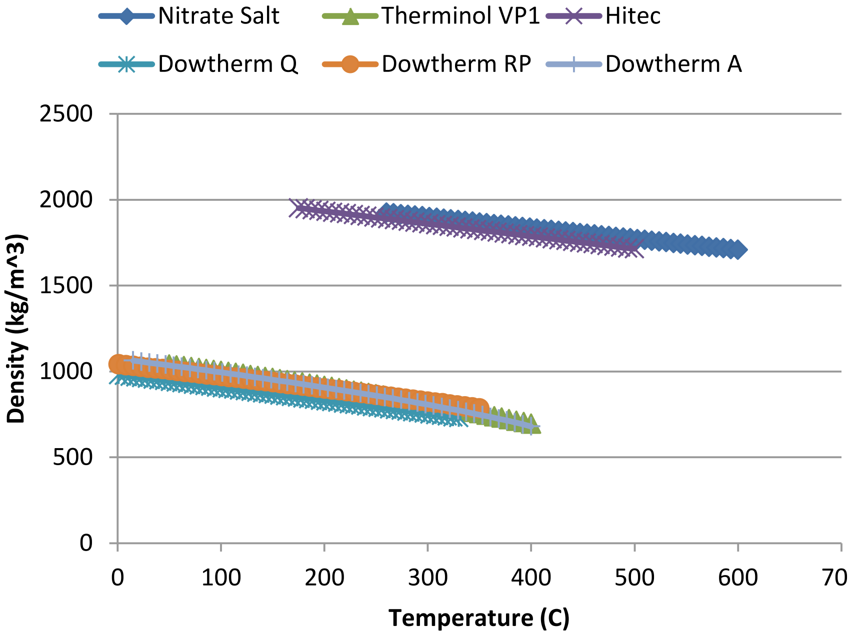
Receivers and Collectors

- **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**

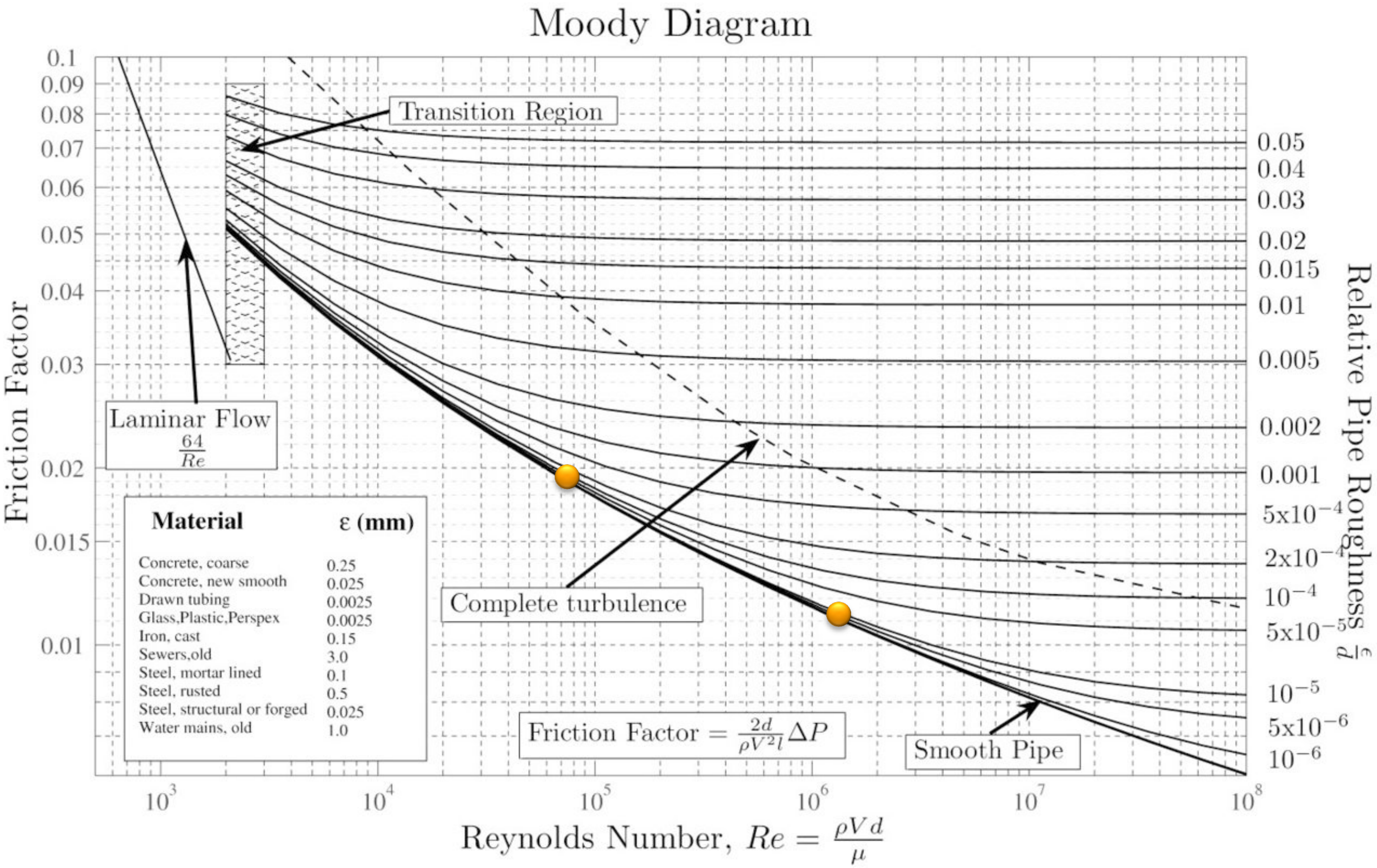




Solar field – Min/Max Flow Rate

- **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



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
Sewers,old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

(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 ΔP_{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)

$$\dot{q}_{loop} = A_{sca}\,\eta_{abs}\,N_{sca}\,I_{bn}$$

$$\dot{q}_{loop} = \dot{m}_s\,c_{ps}\,\Delta T_s$$

$$\dot{m}_s = \frac{A_{sca}\,\eta_{abs}\,N_{sca}\,I_{bn}}{c_{ps}\,\Delta T_s}$$

$$= 6.4\,\frac{kg}{s}$$

$$I_{bn} = 950\,\frac{W}{m^2} \qquad A_{sca} = 470.3\,m^2$$

$$c_{ps} = 1520\,\frac{J}{kg\,K} \qquad \eta_{abs} = 0.689$$

$$\Delta T_s = (550 - 293) = 257\,C$$

(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**

$$l'_{ref} = \frac{\Delta P_{ref}\; 2D}{\rho_s\, V_s^2\; f_{fs}} = 5.75$$

- **The new length is used to update the estimate of No. of SCA's**
  - Pressure highly nonlinear! Be conservative…

$$N'_{sca} = 46?$$

$$l'_{ref} = 2 \rightarrow N'_{sca} = 16$$

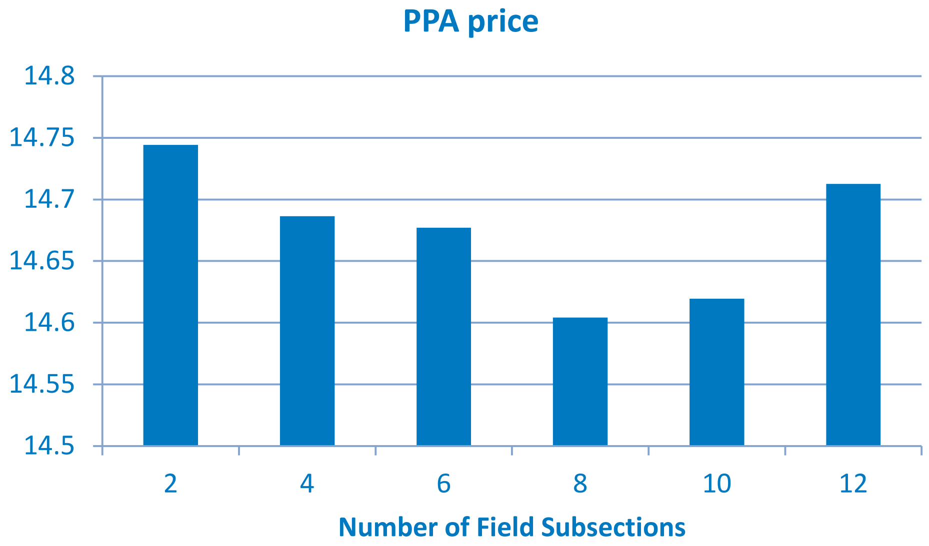
(4) Finally.. Iterate to convergence on L

Iter	$\dot{m}_s$ kg/s	V_s m/s	Re_s	$f_{fs}(Re_s)$	l'	N_{sca}
1	6.4	1.02	75254	0.0195	5.75	16
2	12.8	2.05	151247	0.0165	1.68	14
3	11.2	1.80	132802	0.017	2.11	16

- **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



Power Cycle – Dry Cooling

- **Condenser type =** Air-cooled
- **Ambient temp at design =** 42°C
  - Condensing temperature is $T_{amb} + \Delta T_{ITD} = 58C$
- **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:
    - $\eta_1 = 1 - \frac{58+273.15}{\mathbf{550}+273.15} = 0.5977$
    - $\eta_2 = 1 - \frac{58+273.15}{\mathbf{530}+273.15} = 0.5877$
    - $\eta = 0.412\frac{\eta_2}{\eta_1} = 0.4051$

Power cycle – Other parameters

- **Design gross output =** 167 MWe
  - Increase design gross until the estimated nameplate capacity meets the target
- **Aux heater outlet set temp =** 550°C
  - Not used in this example, but good practice
- **Minimum required startup temp =** 360°C
  - Trade HTF temperature for lower-efficiency cycle operation
  - 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!**
    - Minor changes to reflect updated HTF
- **Storage cost =** 30 $/kWht
- **Power plant =** 1200 $/kWe

Simulation & Results (in SAM)

Optimizing thermal storage and solar multiple

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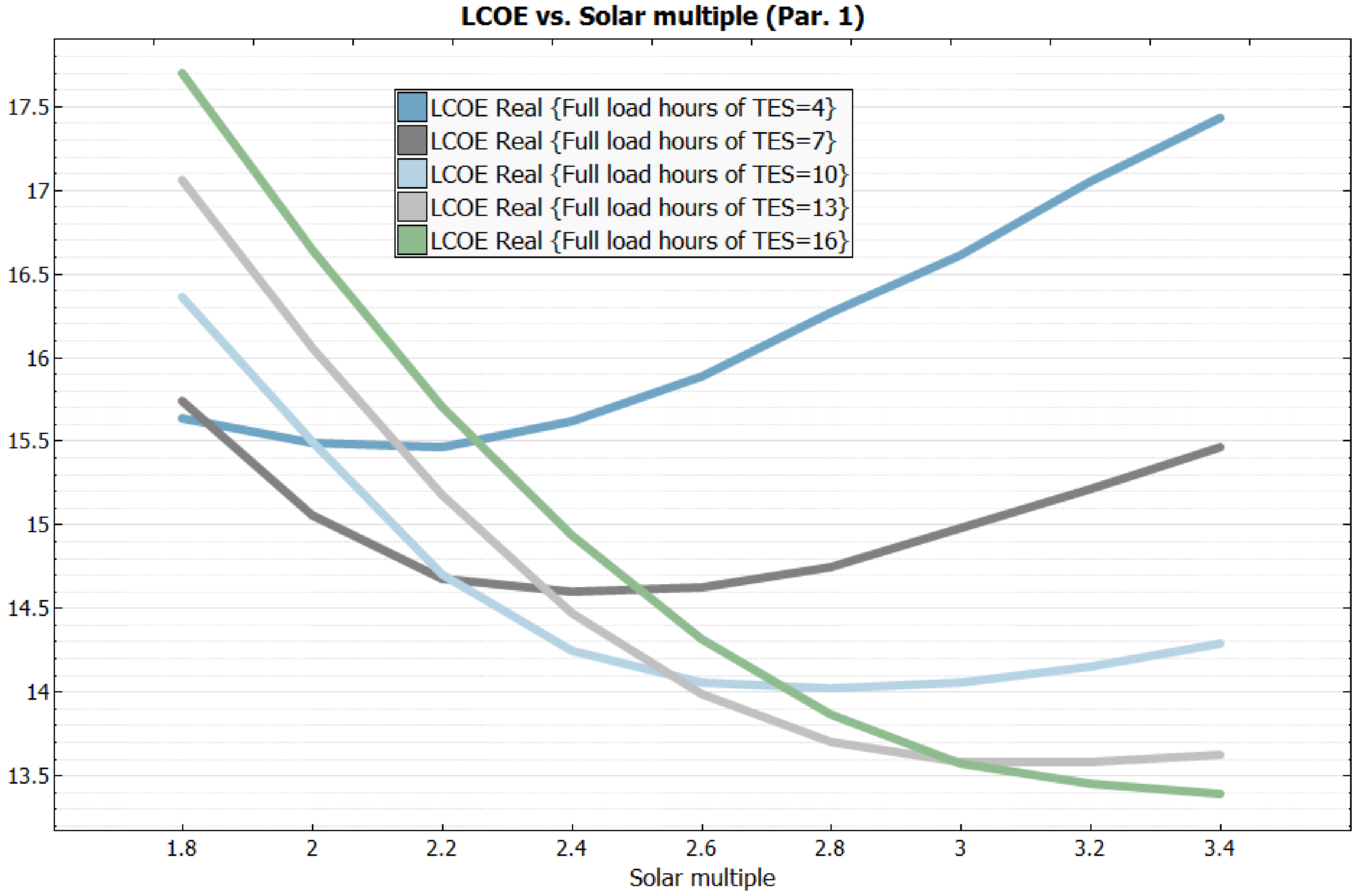

Optimizing…

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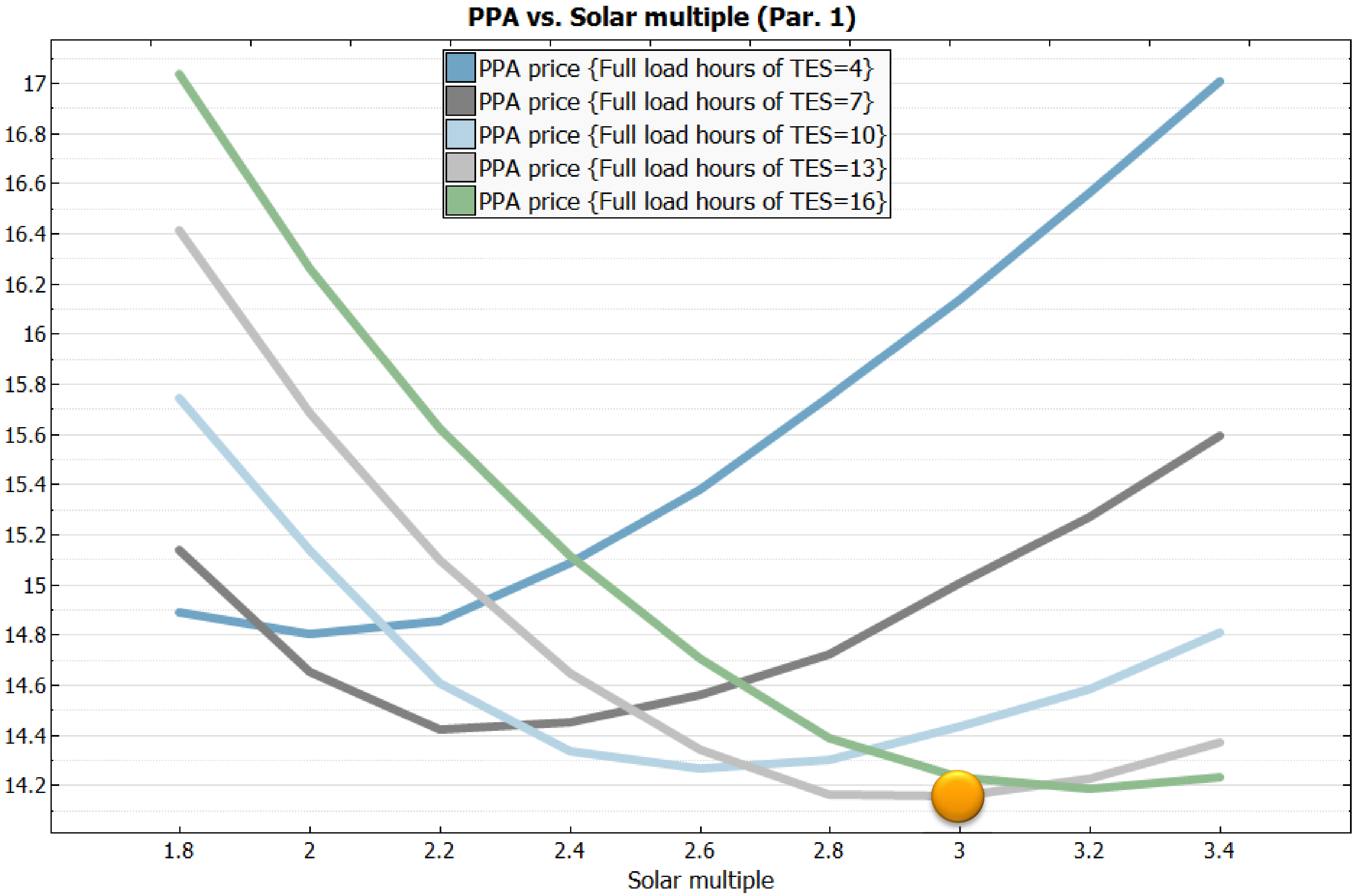

Comparison: MS vs Oil trough

MS Optimized

Metric	Value
Annual Energy	746,036,992 kWh
PPA price	**14.16 ¢/kWh**
LCOE Nominal	16.80 ¢/kWh
LCOE Real	13.58 ¢/kWh
Internal rate of return (%)	19.35%
Minimum DSCR	1.43
Net present value ($)	$137,266,240.00
Calculated ppa escalation (%)	1.00%
Calculated debt fraction (%)	50.00%
Capacity factor	56.70%
Gross to Net Conv. Factor	0.93
Annual Water Usage	141,351 m3
Total Land Area	1961.13 acres

Oil Trough Optimized

Metric	Value
Annual Energy	349,266,368 kWh
PPA price	**15.30 ¢/kWh**
LCOE Nominal	19.24 ¢/kWh
LCOE Real	15.55 ¢/kWh
Internal rate of return (%)	19.50%
Minimum DSCR	1.44
Net present value ($)	$73,059,680.00
Calculated ppa escalation (%)	1.00%
Calculated debt fraction (%)	50.00%
Capacity factor	39.90%
Gross to Net Conv. Factor	0.93
Annual Water Usage	1,317,661 m3
Total Land Area	898.08 acres