U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Technoeconomic Analysis of Heliostat Technologies

Chad Augustine
National Renewable Energy Laboratory

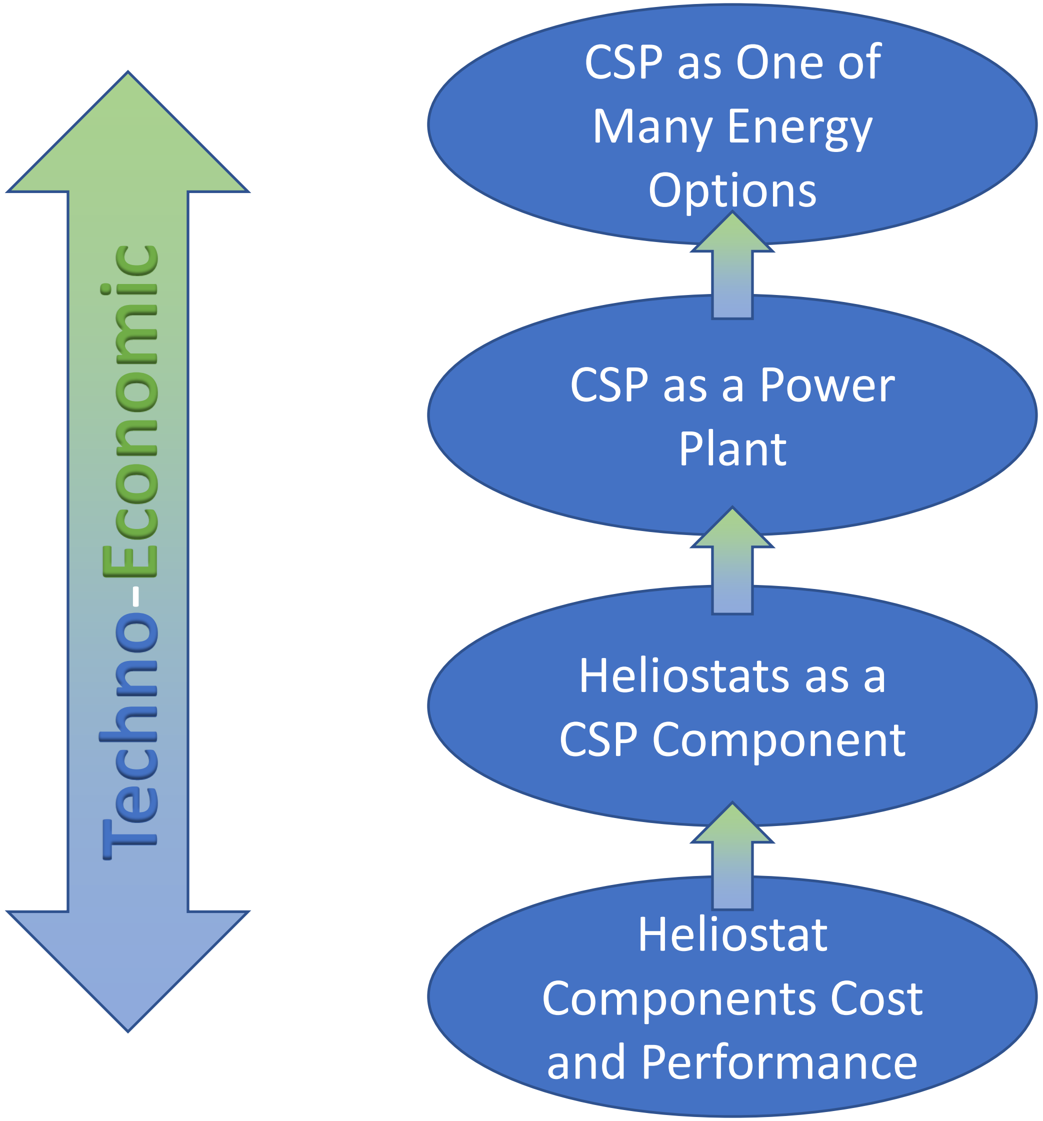
February 3, 2022 • HelioCon Seminar Series

conceptual design • components • integration • mass production • heliostat field

Outline

- Technoeconomic Analysis for CSP
  - Grid-scale
  - Plant-scale
  - Heliostat-scale…
- HelioCon Topic 8: Technoeconomic Analysis Overview
- HelioCon Proposed Baseline Solar Fields
- Preliminary Results

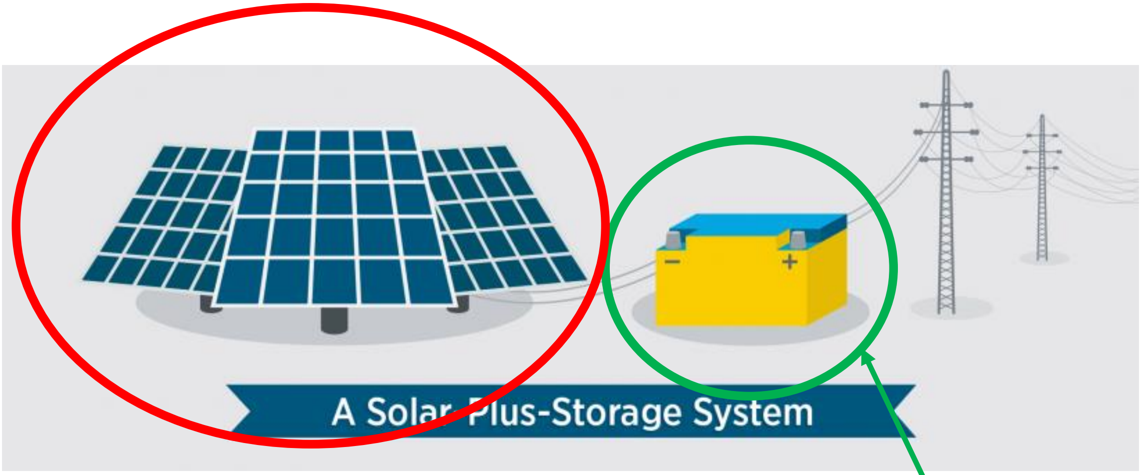
CSP Technoeconomic Analysis

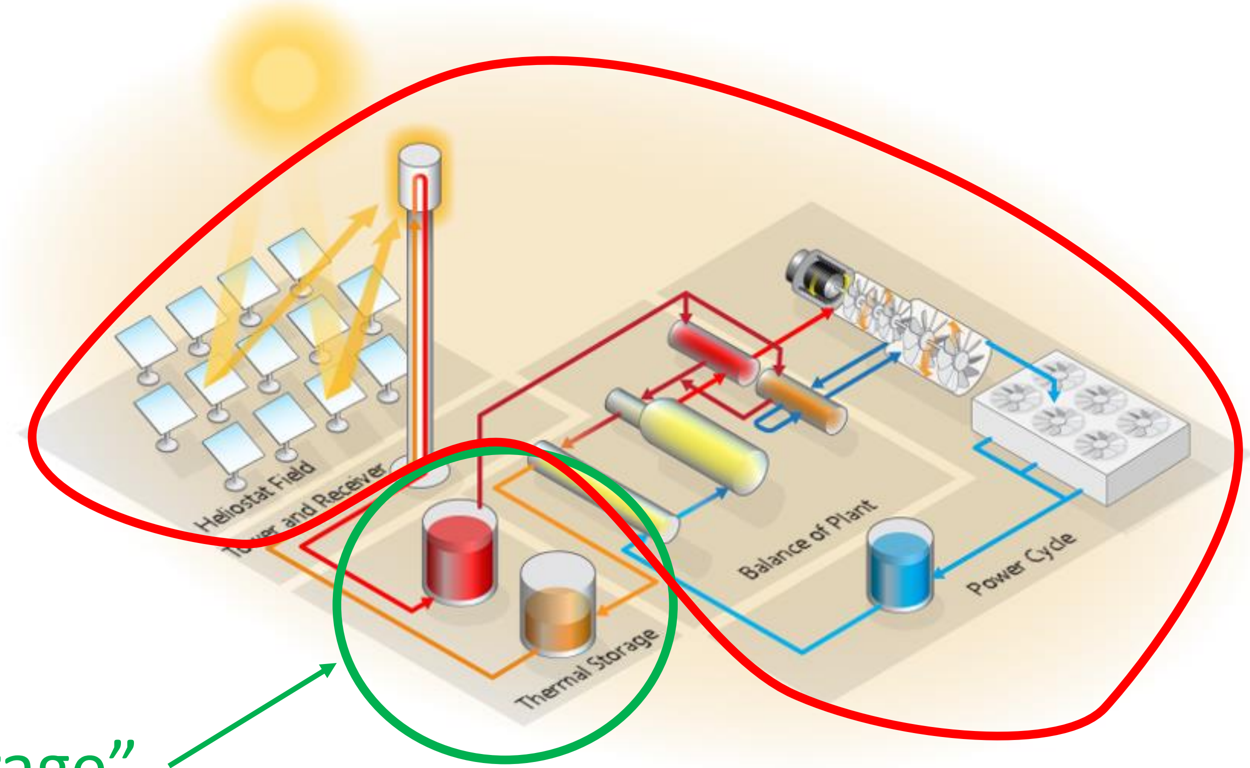


Model Types: Grid Capacity Expansion
Grid Unit-Commitment Dispatch

Key Metrics: Installed Capacity (GW)
Annual Generation (GWh)
Firm Capacity Value ($/kW)

CSP as Energy Option – Grid View





"Storage"

CSP as Energy Option – Grid View

Table 4. Summary of Solar Futures Study Core Scenarios

Scenario Name	**RE & Storage Technologies (ATB 2020)**	**Demand Flexibility (EFS)**	**Electricity Demand**	**Policies**
Reference	Moderate	None	AEO2020 Reference	Existing policies as of June 2020
Decarbonization (Decarb)	Advanced			95% reduction in grid CO_2 emissions from 2005 levels by 2035, 100% by 2050
Decarbonization with Electrification (Decarb+E)		Enhanced	EFS High	

Source: NREL *Solar Futures Study* (DOE 2021)

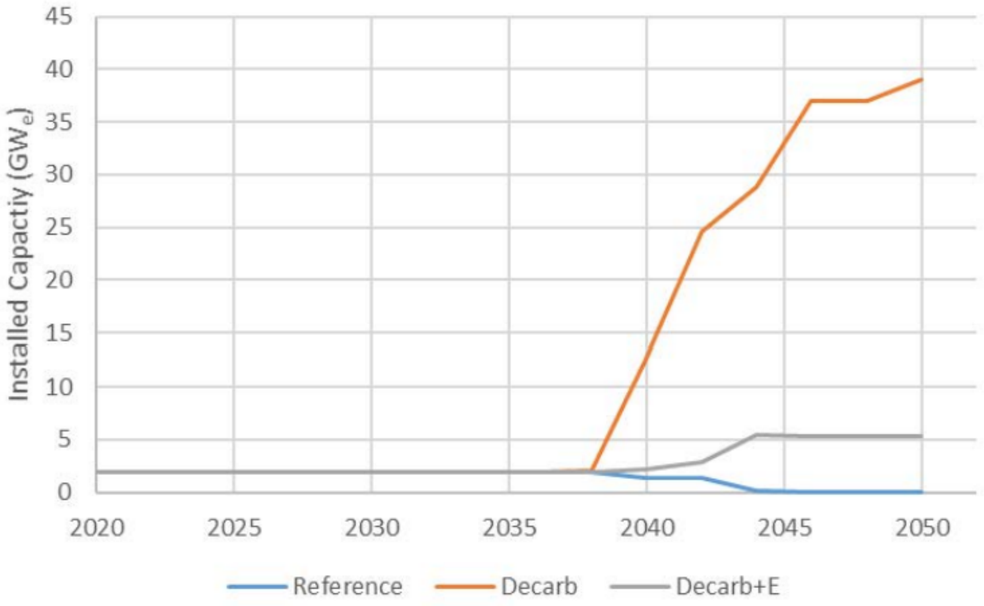
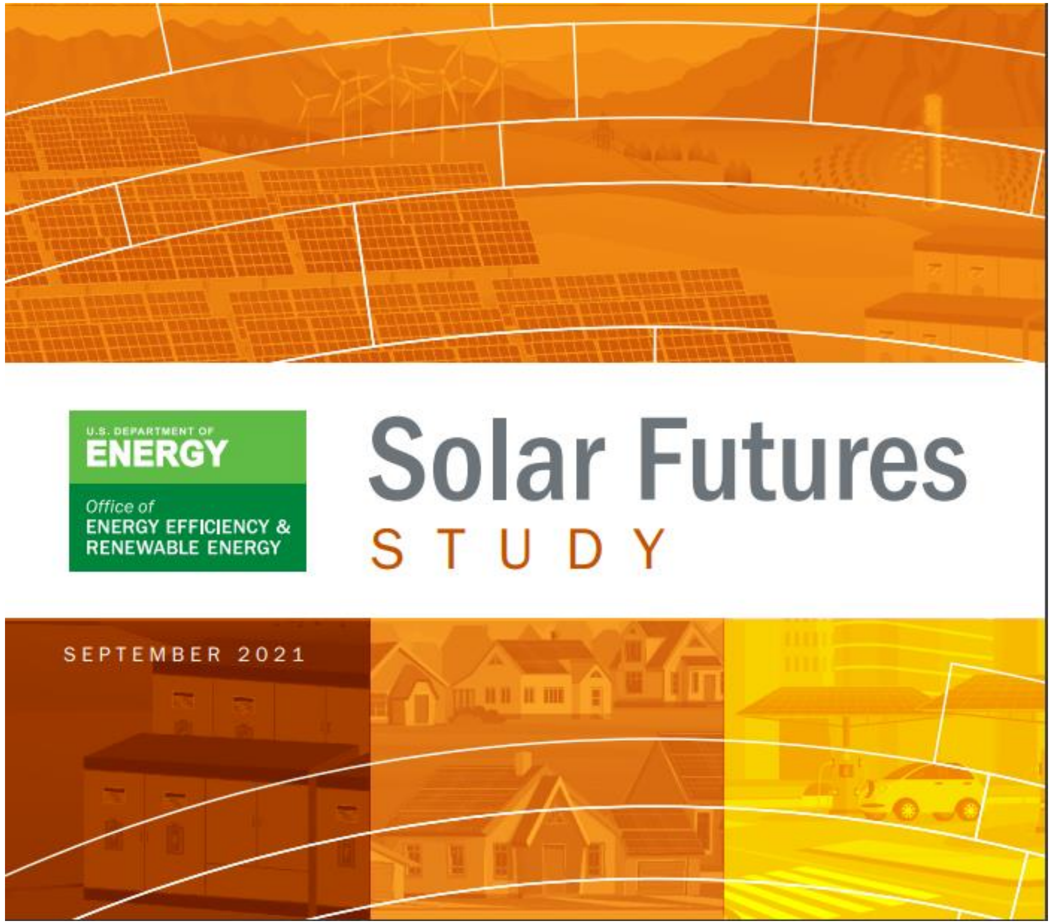


Figure 17. CSP deployment in Solar Futures Study core scenarios, 2020–2050



CSP as Energy Option – Grid View

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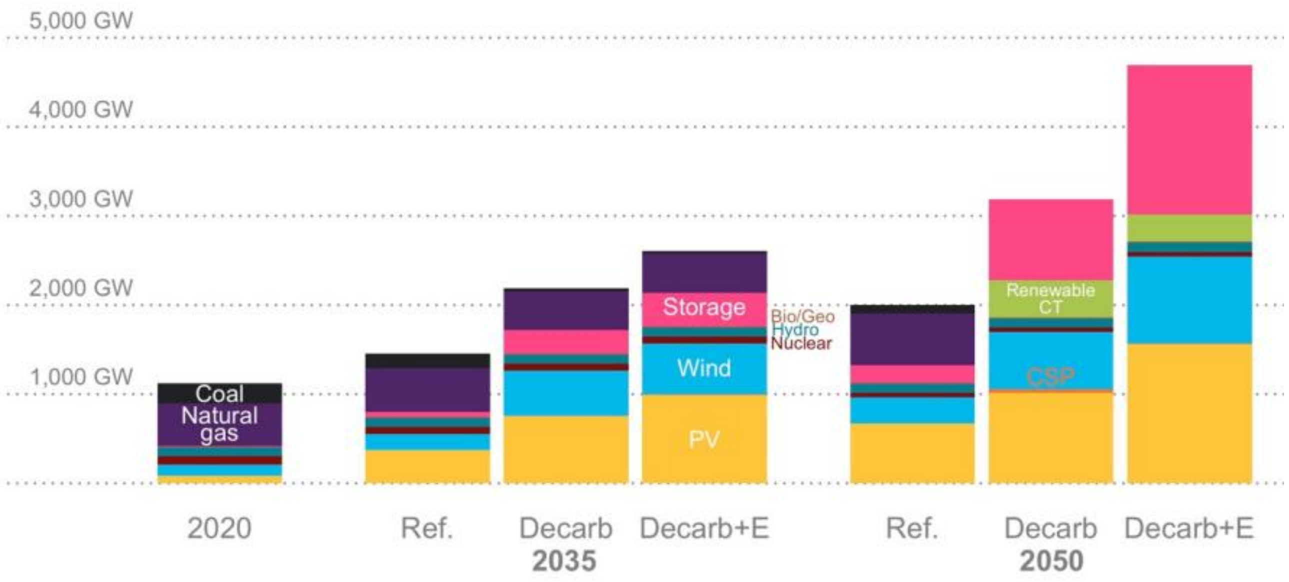
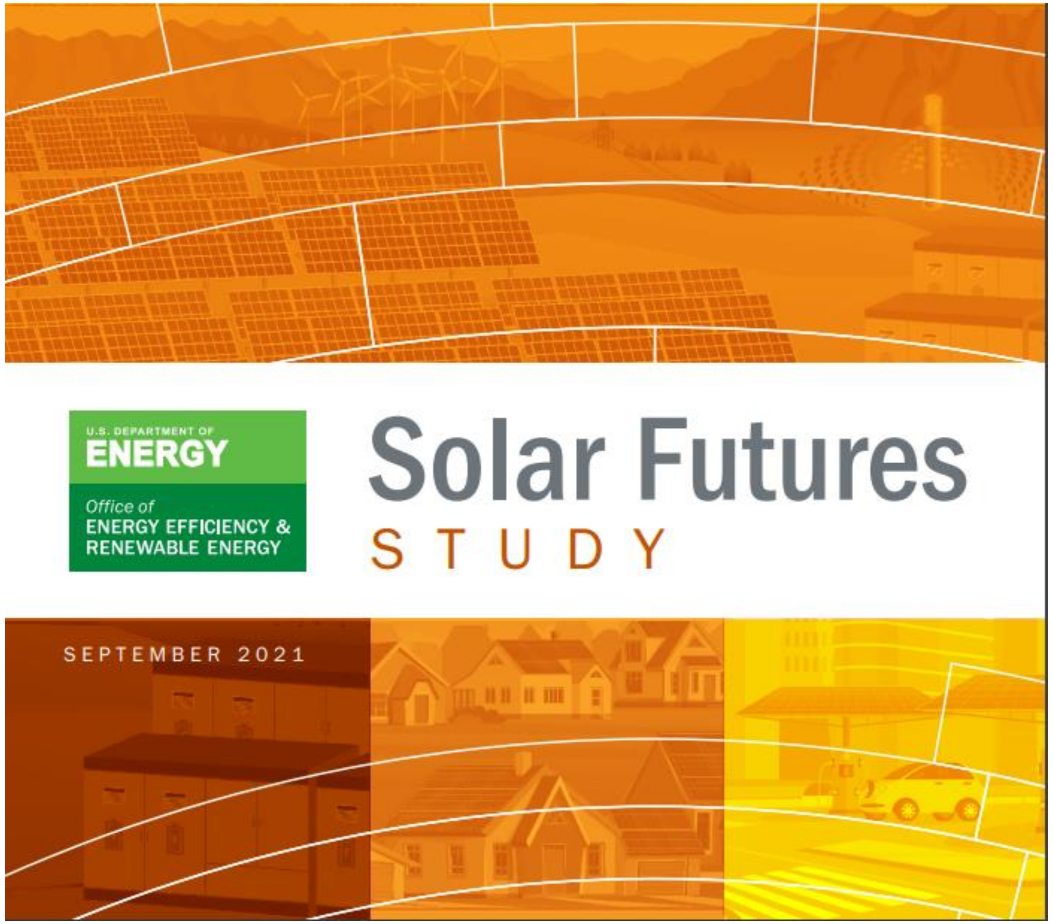


Figure 2 - 4. Capacity by technology in 2020, 2035, and 2050 in core scenarios



CSP as Energy Option – Grid View

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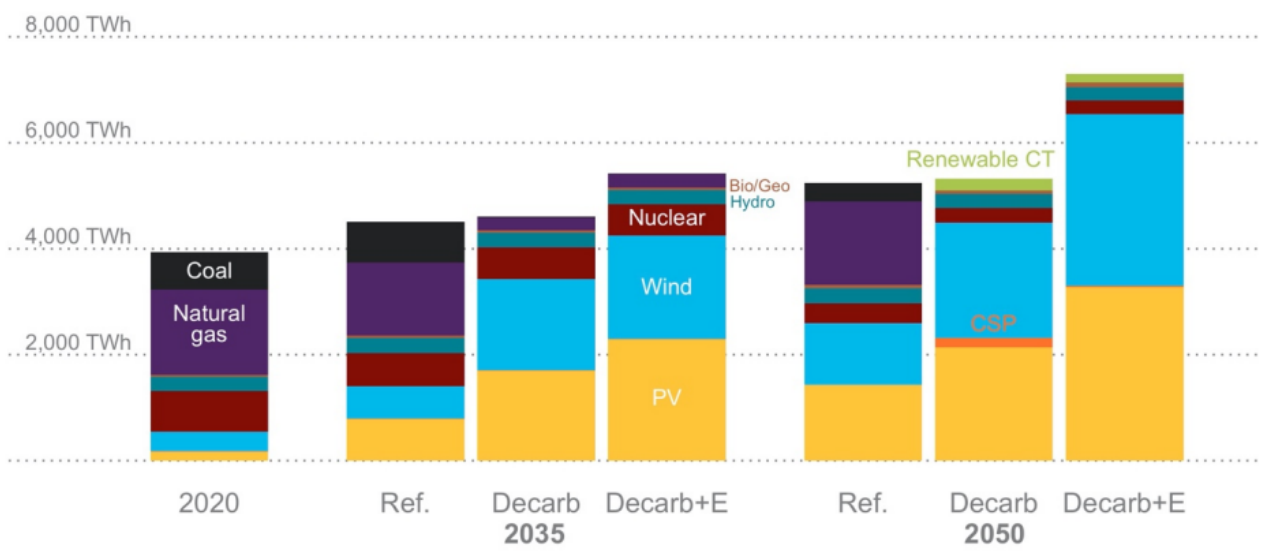
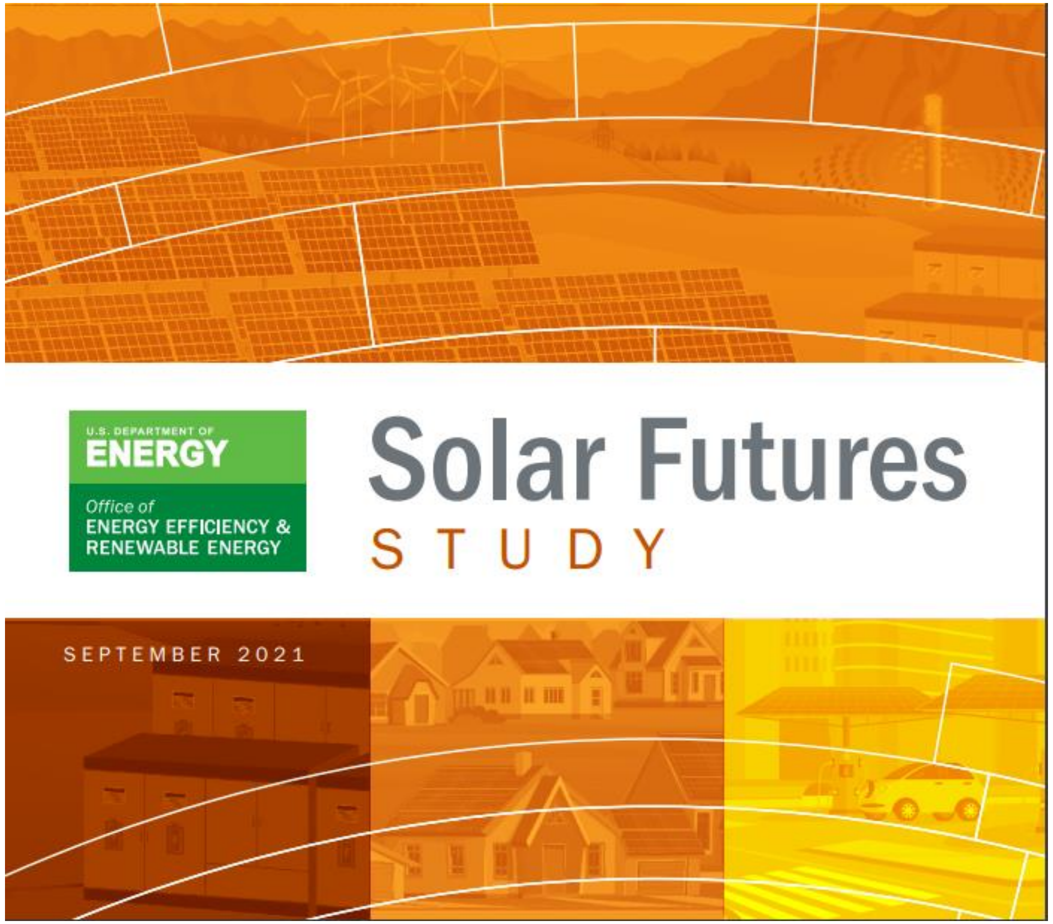


Figure 2 - 3. Generation by technology in 2020, 2035, and 2050 in core scenarios

Bio = biomass, Geo = geothermal, Hydro = hydropower, CT = combustion turbine. Hydro includes pumped hydro-storage.



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CSP as Energy Option – Grid View

- Energy storage projections in the US are dominated by short-term (2-4 hours) storage needs
- As RE penetration increases, longer storage options compete better
- As 95% CO2 reduction is approached, need for firm capacity value increases

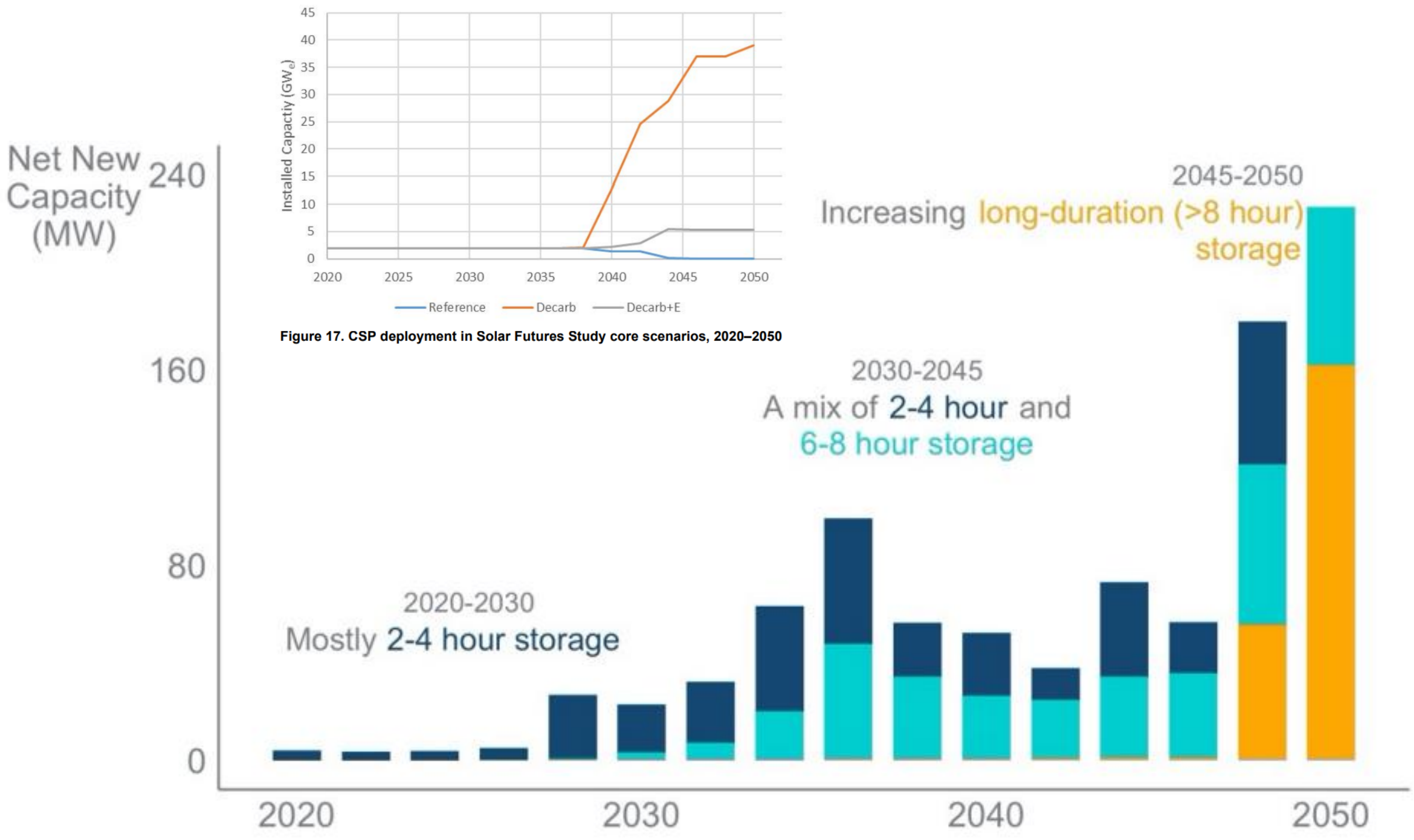
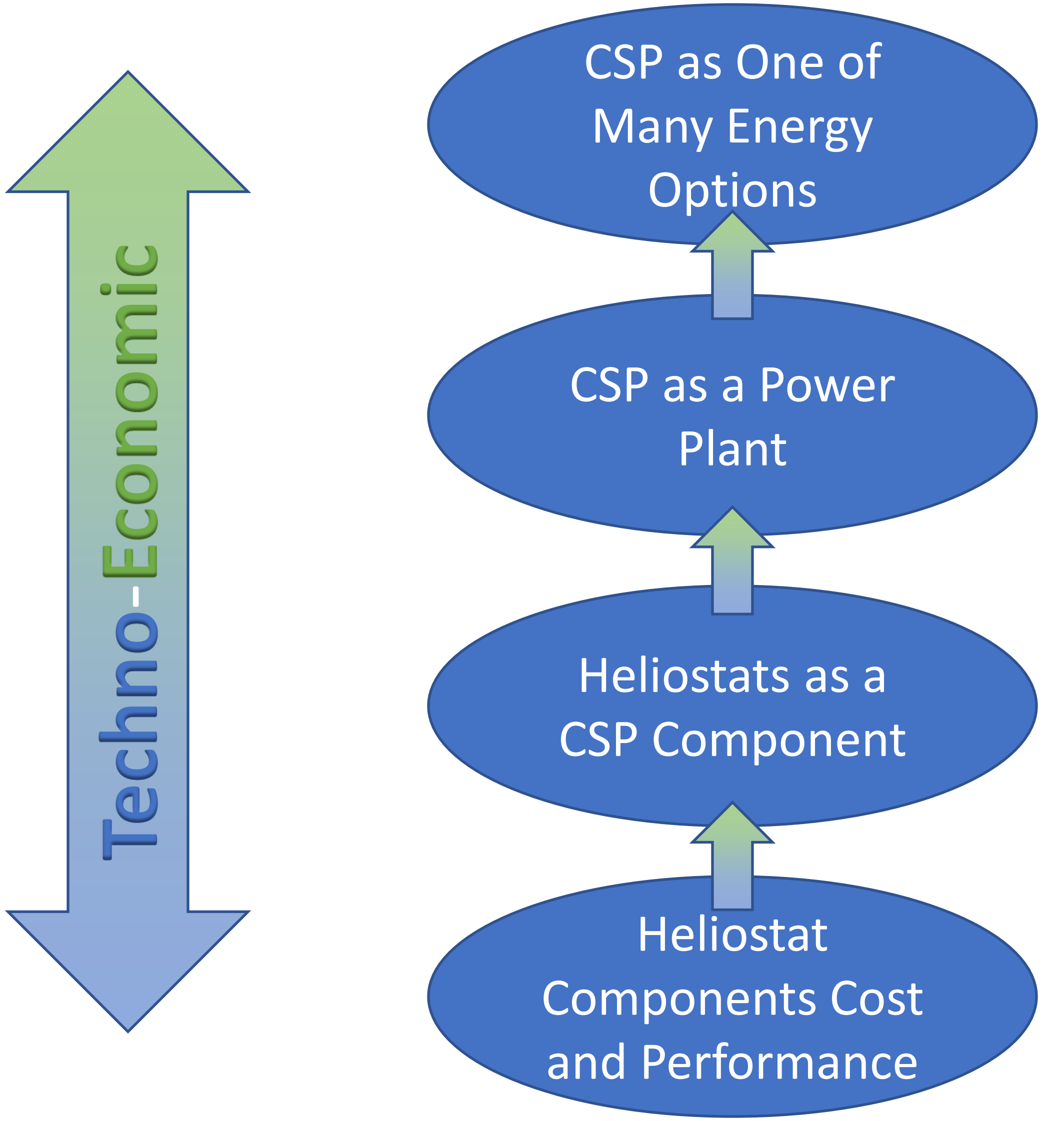


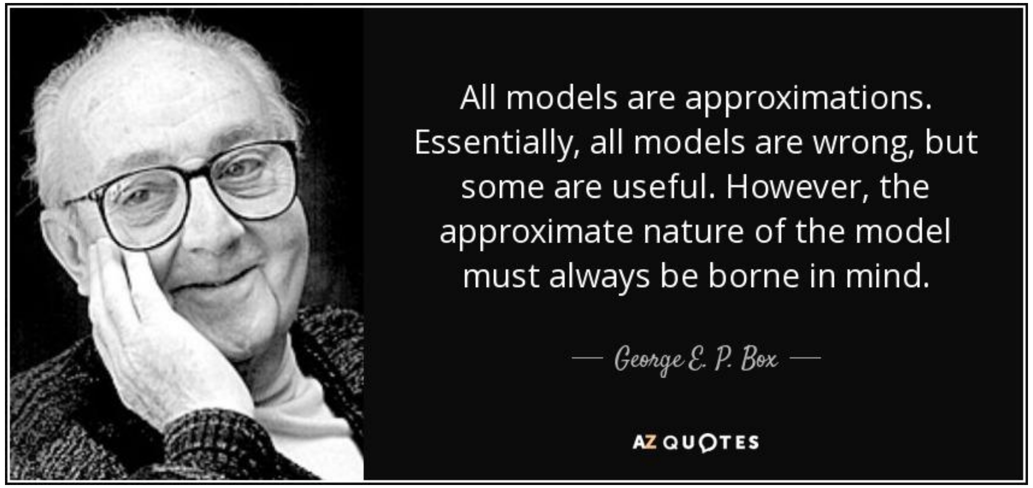
Figure 5 - 4. Storage by duration in the Decarb scenario

CSP Technoeconomic Analysis



Model Types: Power Plant/System Model

Key Metrics: LCOE ($/kWh), NPV
Overnight Capital Costs ($/kW)
Capacity Factor (%)



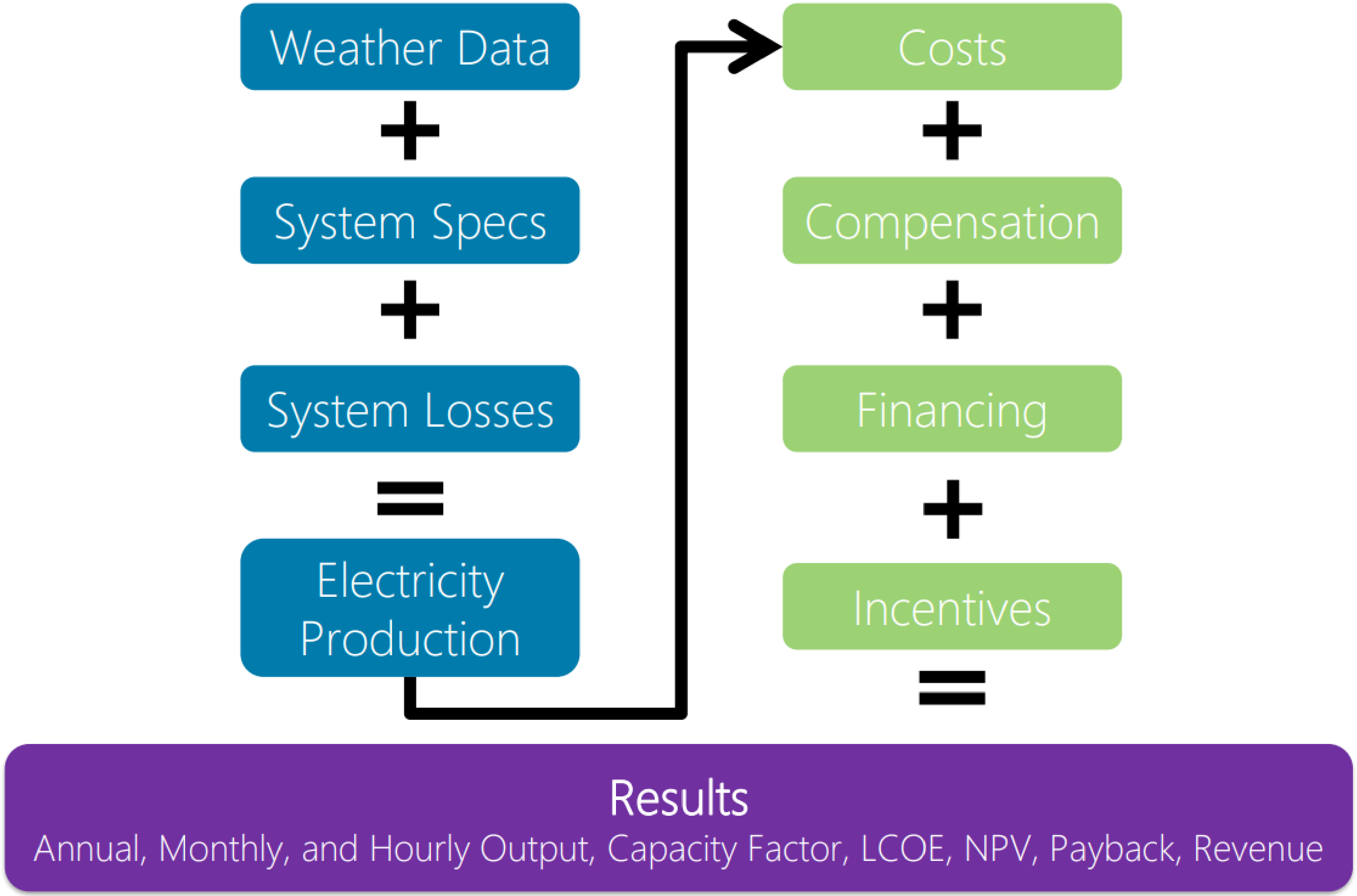
System Advisor Model (SAM)

Technologies

- Photovoltaics
  - Detailed & PVWatts
- Battery Storage
- Concentrating solar power
- Fuel cell-PV-battery
- Wind
- Marine Energy
- Geothermal
- Solar water heating
- Biomass

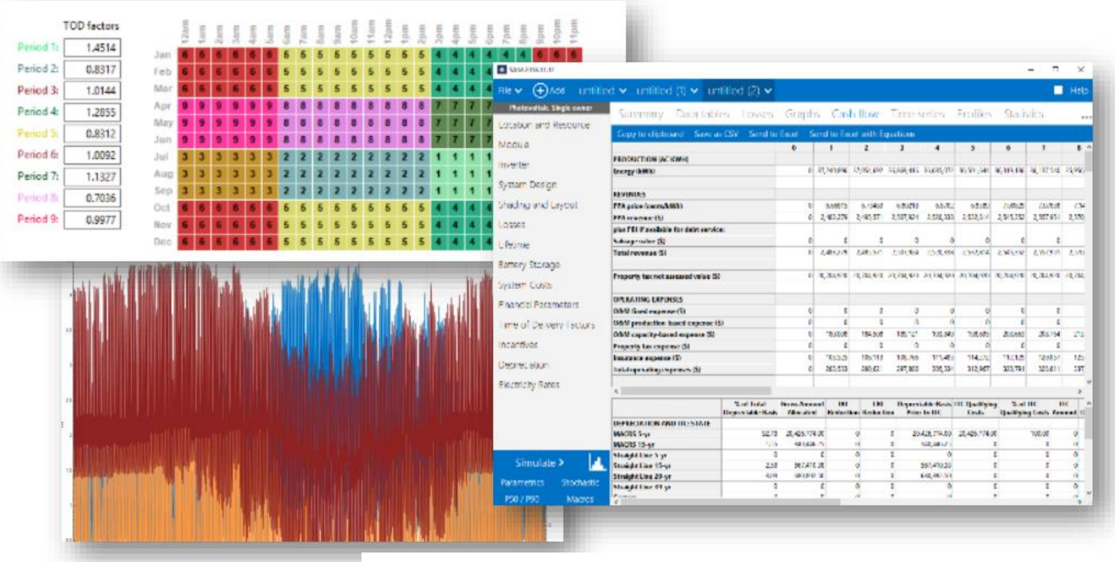
Financial

- Behind-the-meter
  - residential
  - commercial
  - third-party owned
- Power purchase agreements
  - single owner
  - equity flips
  - sale-leaseback
- Host/developer
- Merchant plant
- Simple LCOE calculator



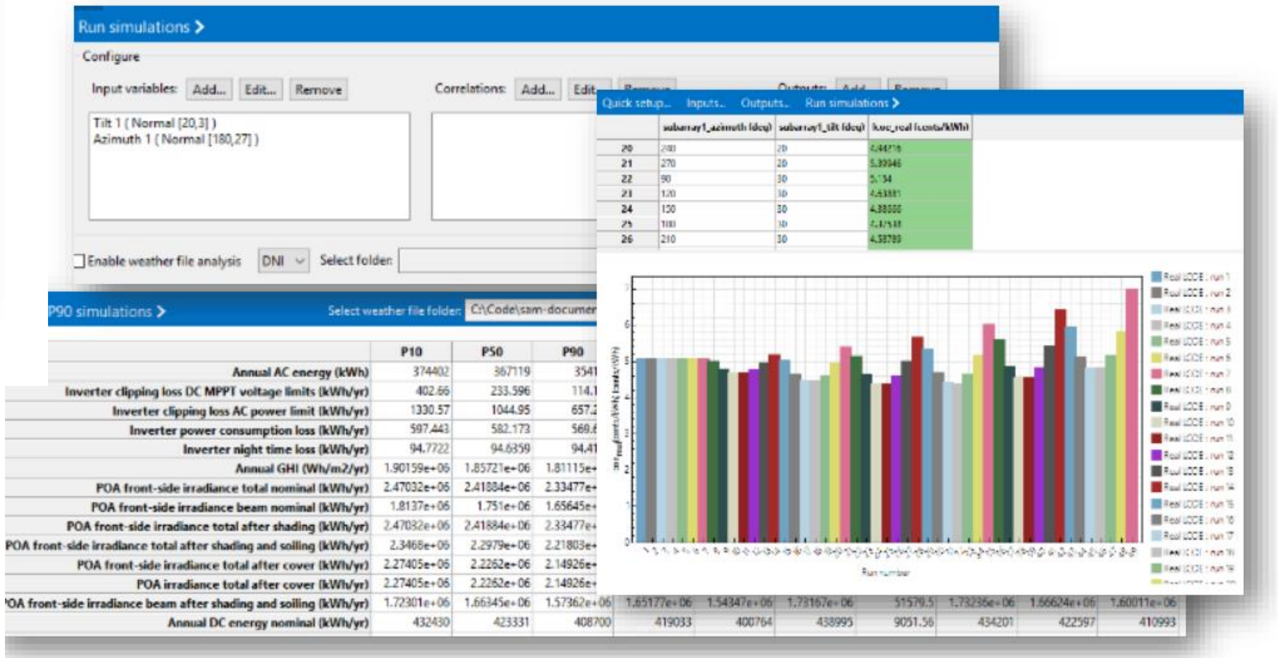
System Advisor Model (SAM)

No other tool provides detailed, *time-based* financial modeling across multiple market sectors, including complex utility rates, combined with detailed performance modeling



- ✓ Flexible
- ✓ Transparent
- ✓ Collaborative

Built-in parametric, stochastic, probability of exceedance P50/P90), and scripting features enable complex questions to be answered quickly and easily



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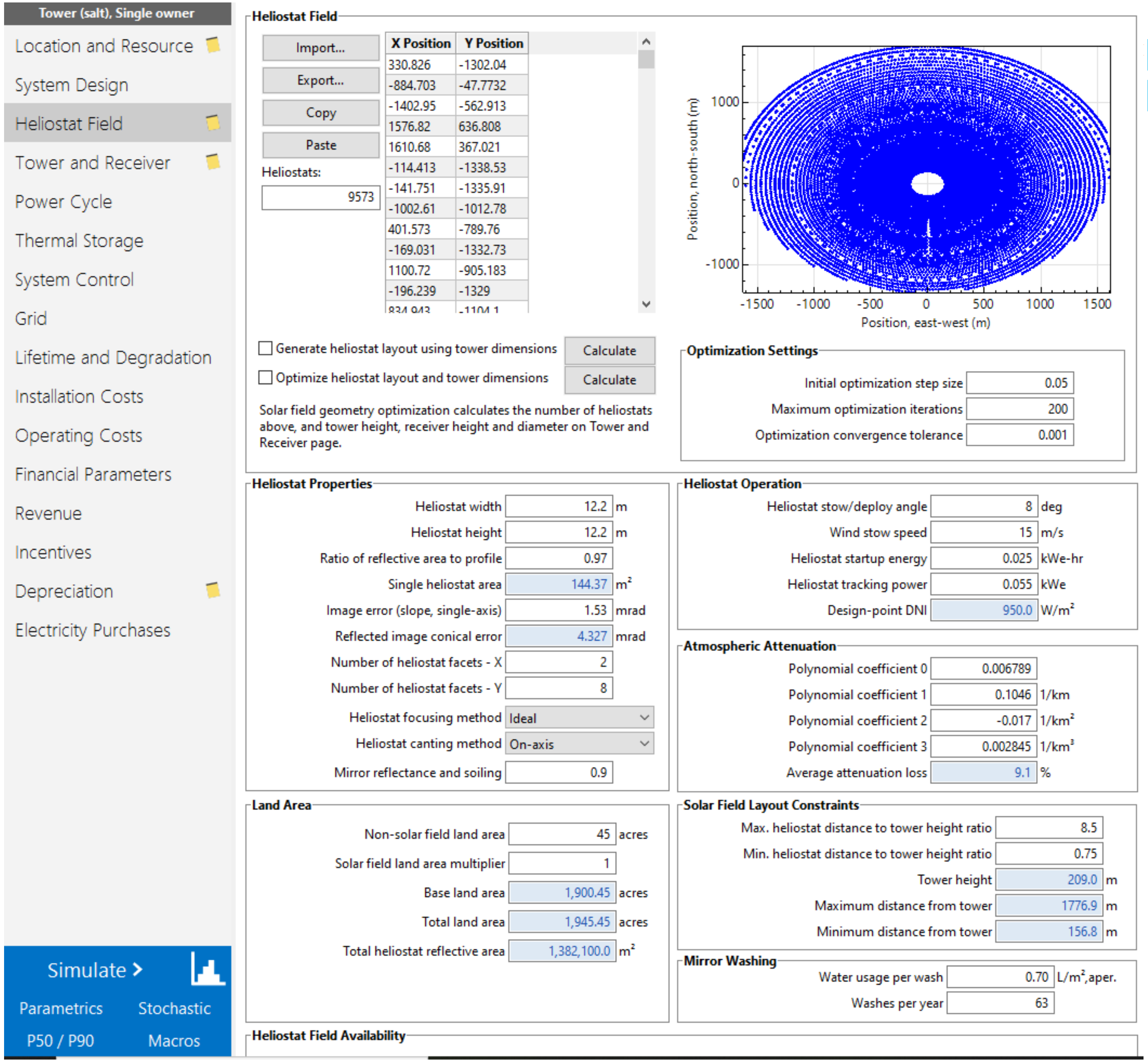
SAM
Power Tower CSP

- "Modeling Power Towers in SAM" https://www.youtube.com/watch?v=xVILbvR8MkM
- Inputs grouped by tabs on left
- Uses SolarPILOT to optimize field, tower height, and receiver dimensions

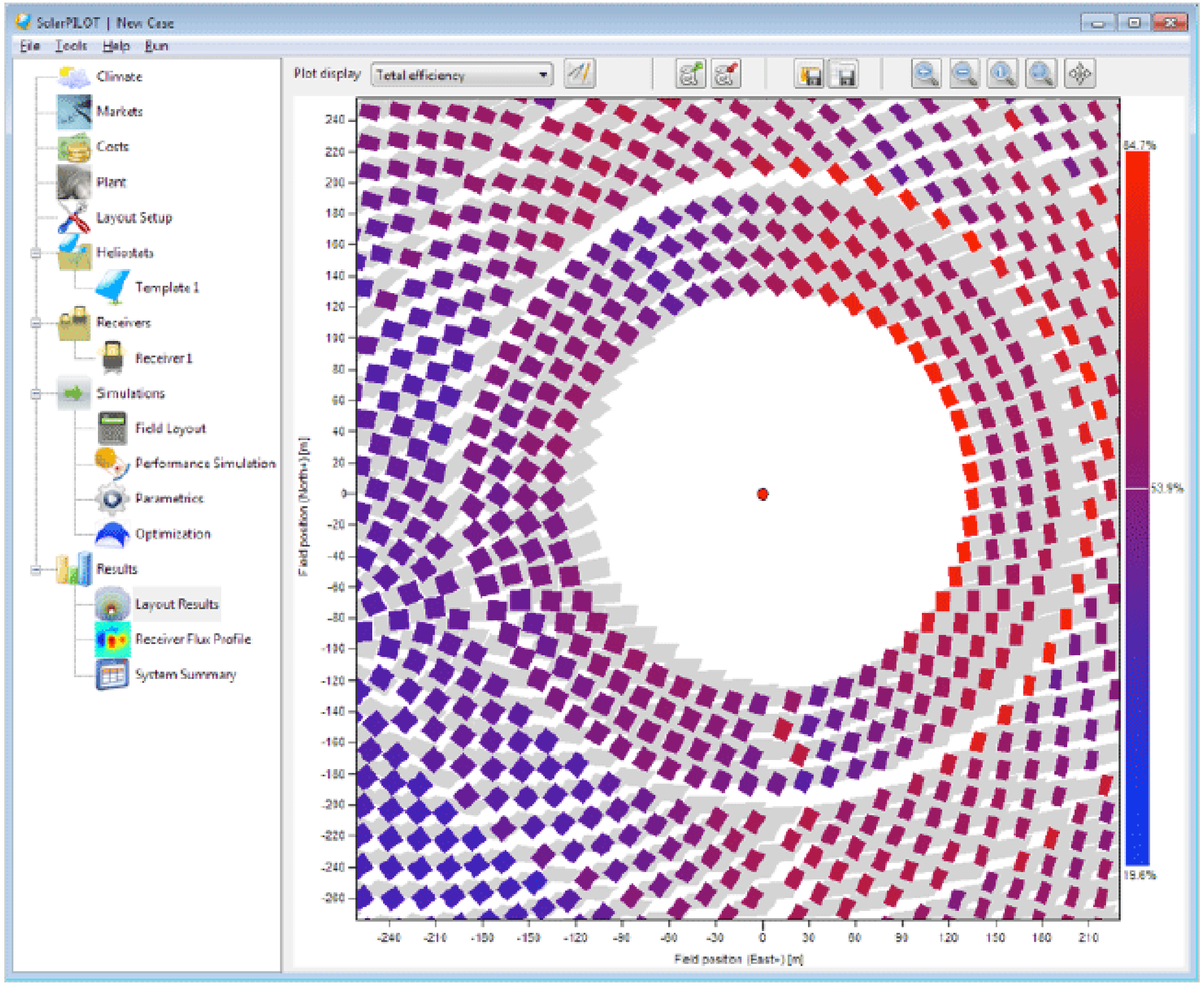


SolarPILOT

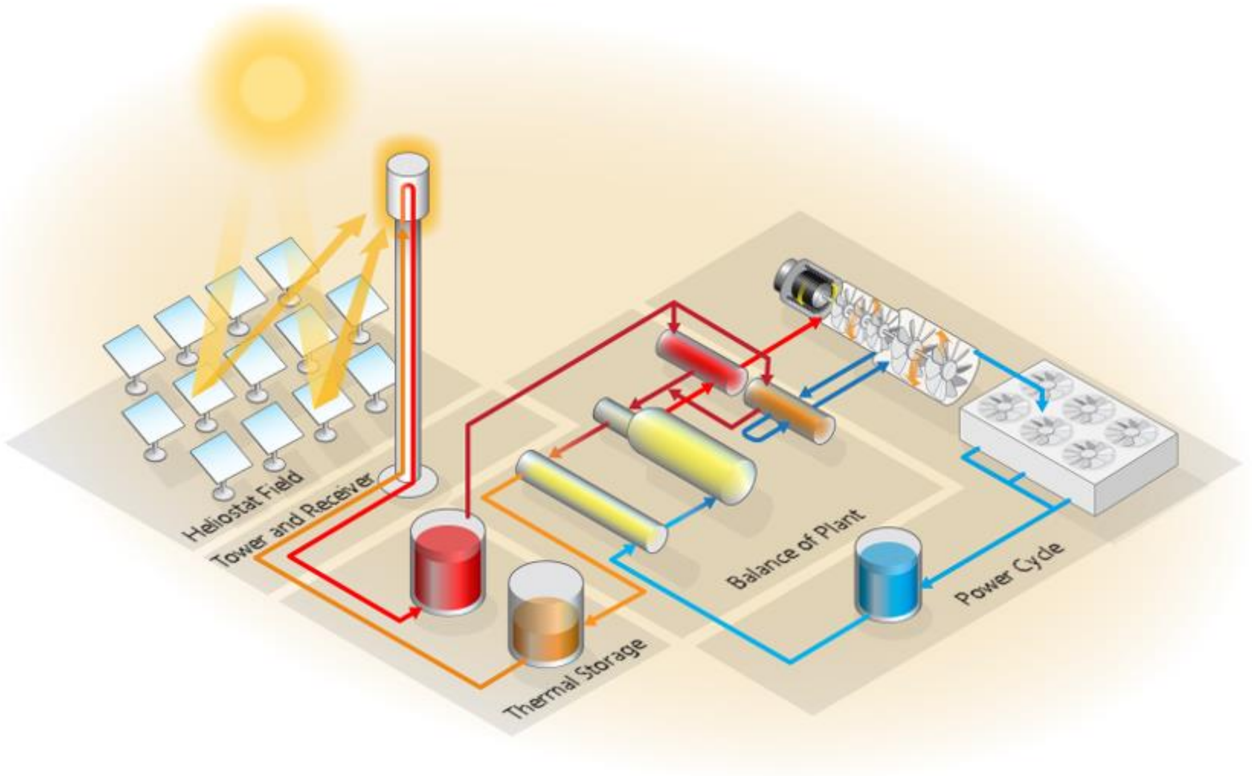
"Overview of NREL's SolarPilot(TM) and SolTrace Open-source Software"
https://www.youtube.com/watch?v=wiYV2VLqr_k

Solar Power Tower Integrated Layout and Optimization Tool (SolarPILOT)

- Create heliostat layouts
- Simulate receiver flux profiles
- Optimize tower, receiver, and layout configurations
- Integrated SolTRACE ray-tracing engine
- Accessible by external programs
- Open source



CSP as a Power Plant




NREL

The Role of Concentrating Solar-Thermal Technologies in a Decarbonized U.S. Grid

Chad Augustine, Craig Turchi, and Mark Mehos

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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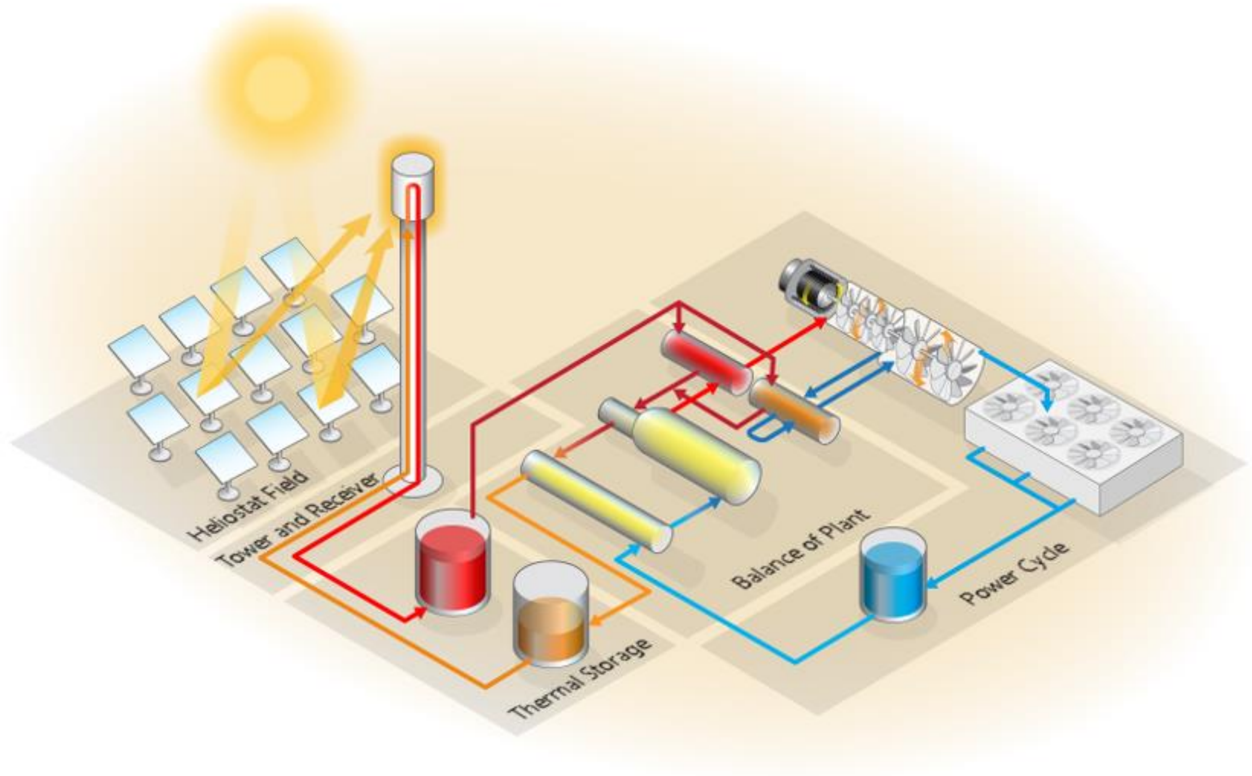
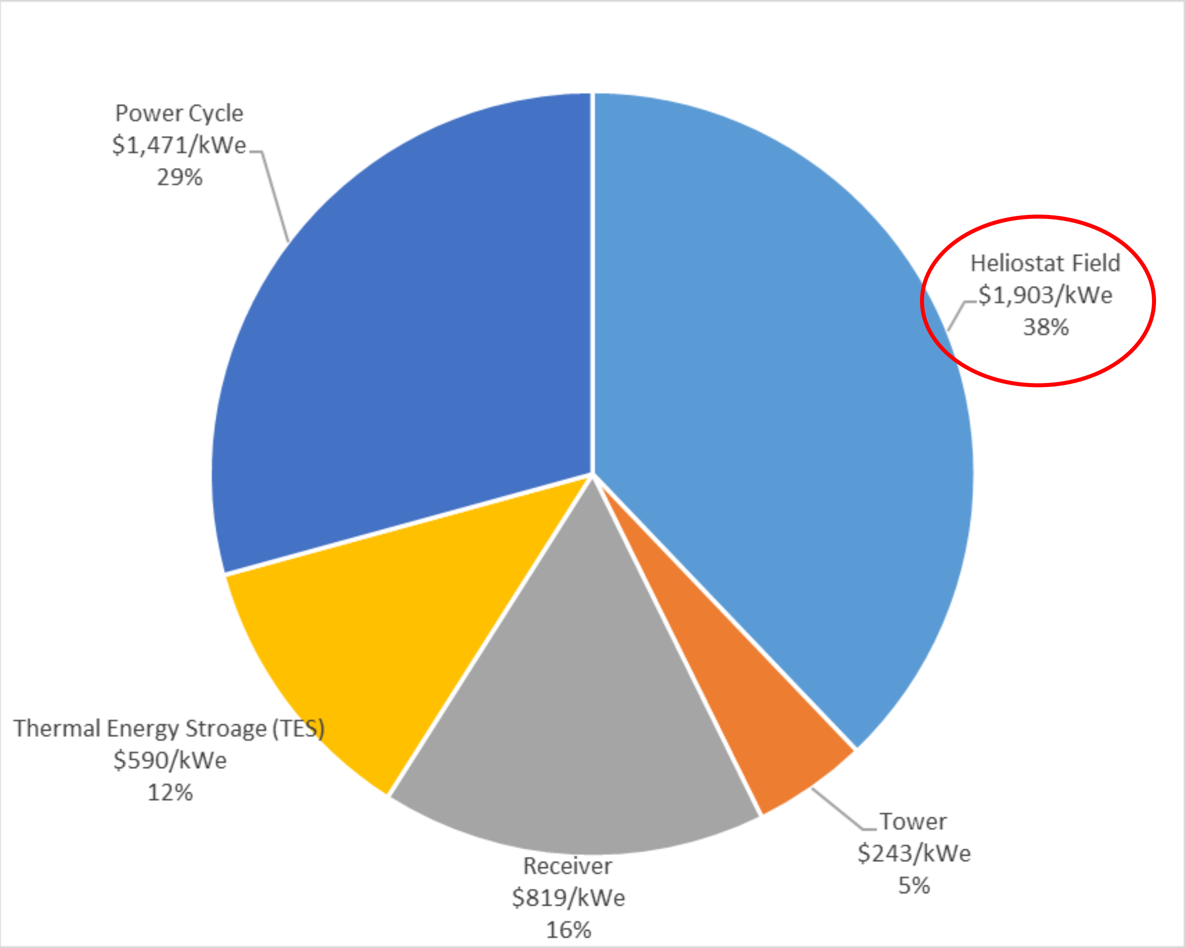
Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-80574
September 2021

CSP as a Power Plant

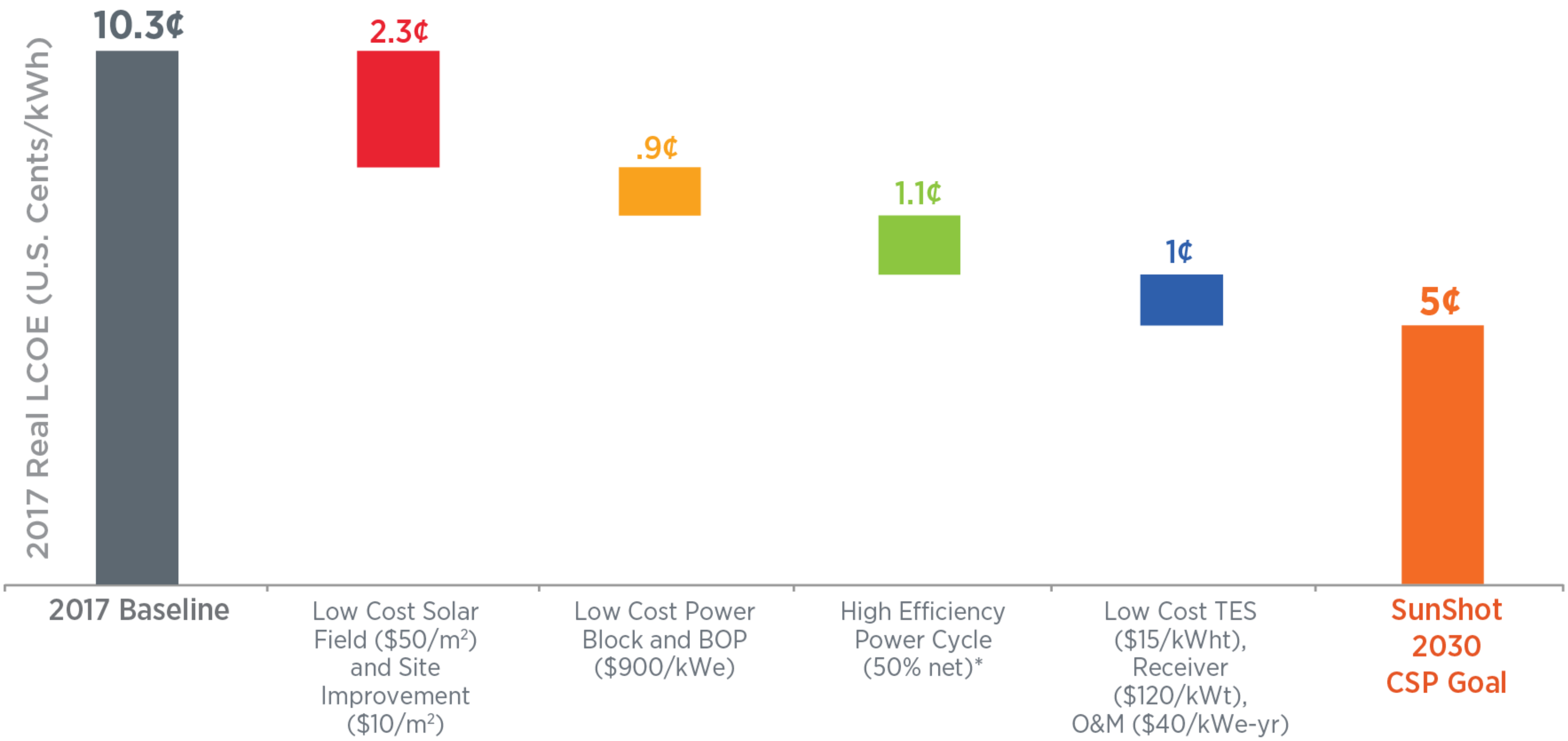




Direct Capital Costs for 100 MWe Gen2 CSP Plant

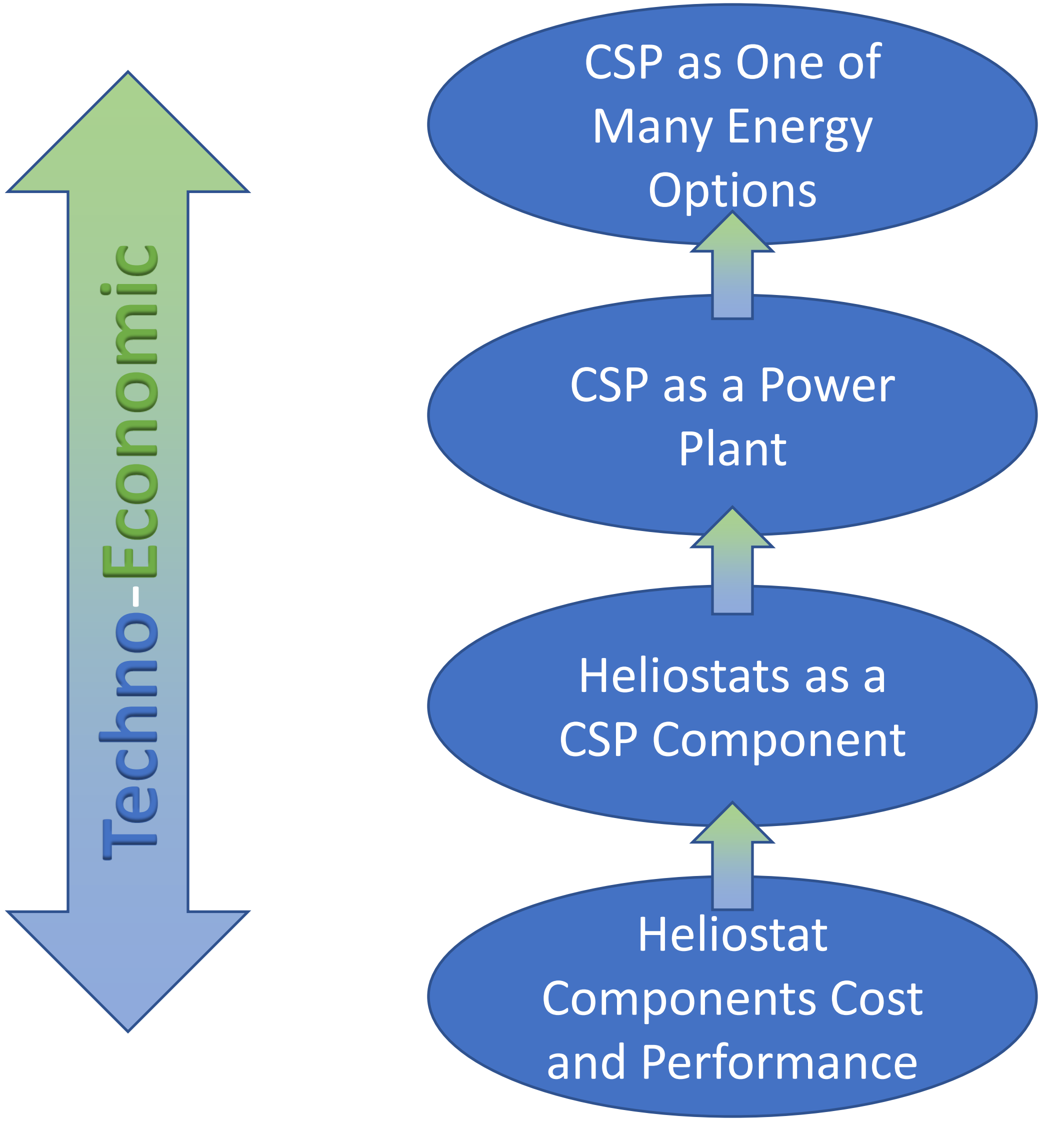
Excludes indirect costs, contingency, and sales tax

A Pathway To $0.05 per kWh for CSP



*Assumes a gross to net conversion factor of 0.9

CSP Technoeconomic Analysis



Model Types: Bottom Up
Top Down

Key Metrics: Installed Cost ($\$/m^2$)
O&M Costs ($\$/m^2$/year)
Heliostat Performance Metrics

Heliostat Analysis Modes

- Bottom-Up Analysis
  - In-depth, expert-level analysis of heliostat based on its components
  - Describe heliostat design, components, construction, performance, etc. in as much detail as possible
  - Goal is to “build” heliostat in as much detail as possible
  - Used to develop detailed cost estimates and identify cost drivers, key components, and specific opportunities for improvement
- Top-Down Analysis
  - High-level view of heliostat – break it down into its key metrics
  - Blackbox-ish, as simple a description as necessary
  - Goal is to identify how heliostat cost and performance affects larger system
  - Used to identify research areas and quantify their potential impact

Bottom-Up Cost Analysis

- Bottom-up cost estimate for sbp Stellio (commercial) and Solar Dynamics Drop-C (advanced) heliostats
- Uses Design for Manufacture and Assembly (DFMA)
- Assumes field for 80 MWe CSP power tower with 12-16 hours TES, ~1.1 million m^2 of heliostat surface area


NREL

Cost Update: Commercial and Advanced Heliostat Collectors

Parthiv Kurup, Sertaç Akar, Stephen Glynn, Chad Augustine, and Patrick Davenport

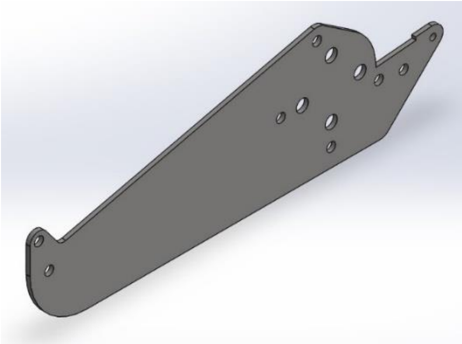
National Renewable Energy Laboratory

Technical Report
NREL/TP-7A40-80482
February 2022

Bottom-Up Cost Analysis

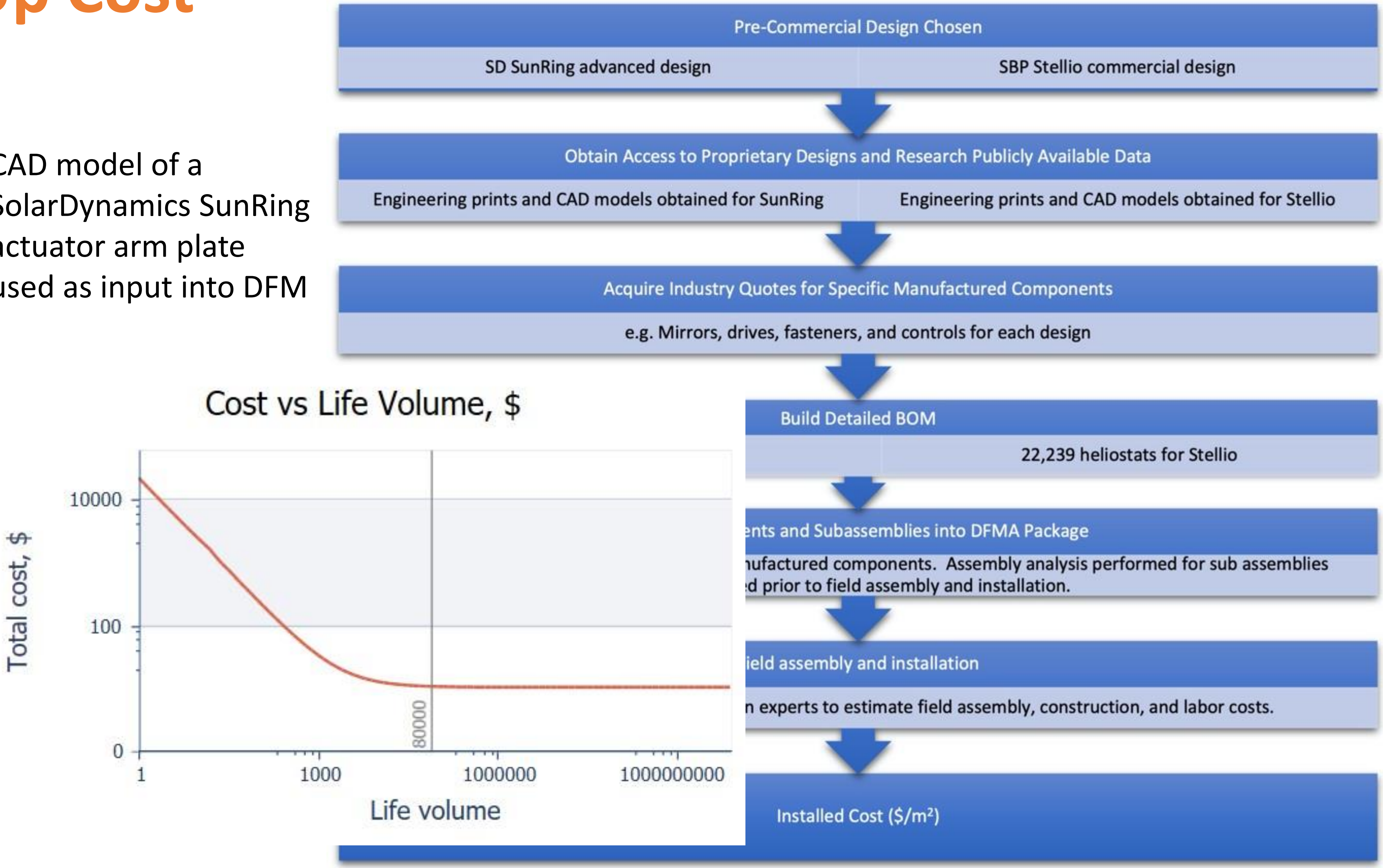
- Design for Manufacture and Assembly (DFMA)
  - Model the manufacturing process for each heliostat component (bill of materials – BOM)
  - Includes assembly costs (ex. – welding)
  - Accounts for manufacturing volume
- Cost estimates for purchased components from manufacturers
- Includes on-site construction and installation costs

Bottom-Up Cost Analysis

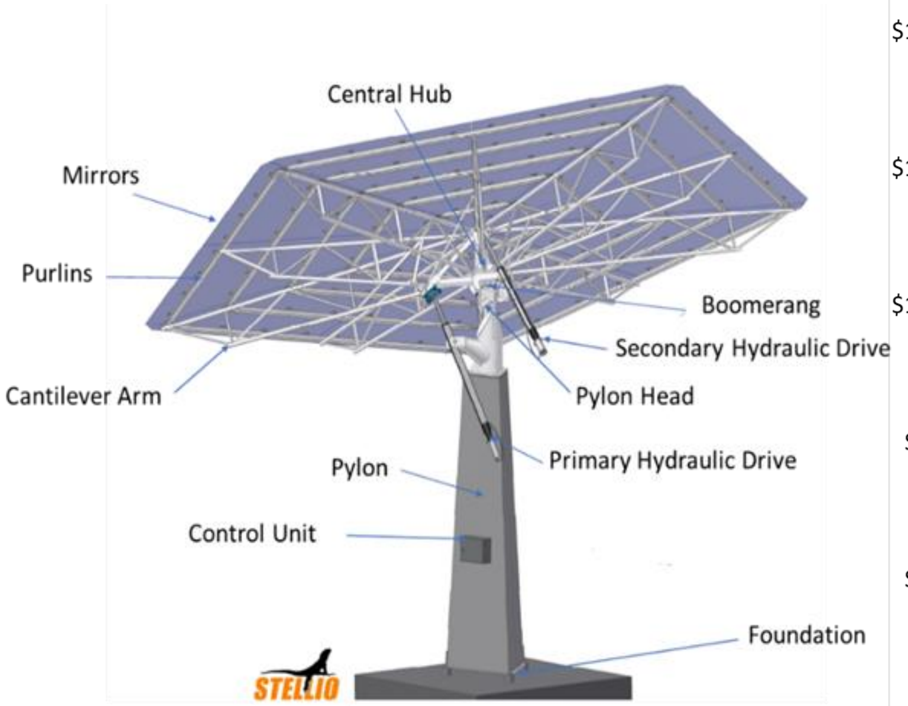


CAD model of a SolarDynamics SunRing actuator arm plate used as input into DFM

Effects of manufacturing the SunRing actuator arm plate at various production scales

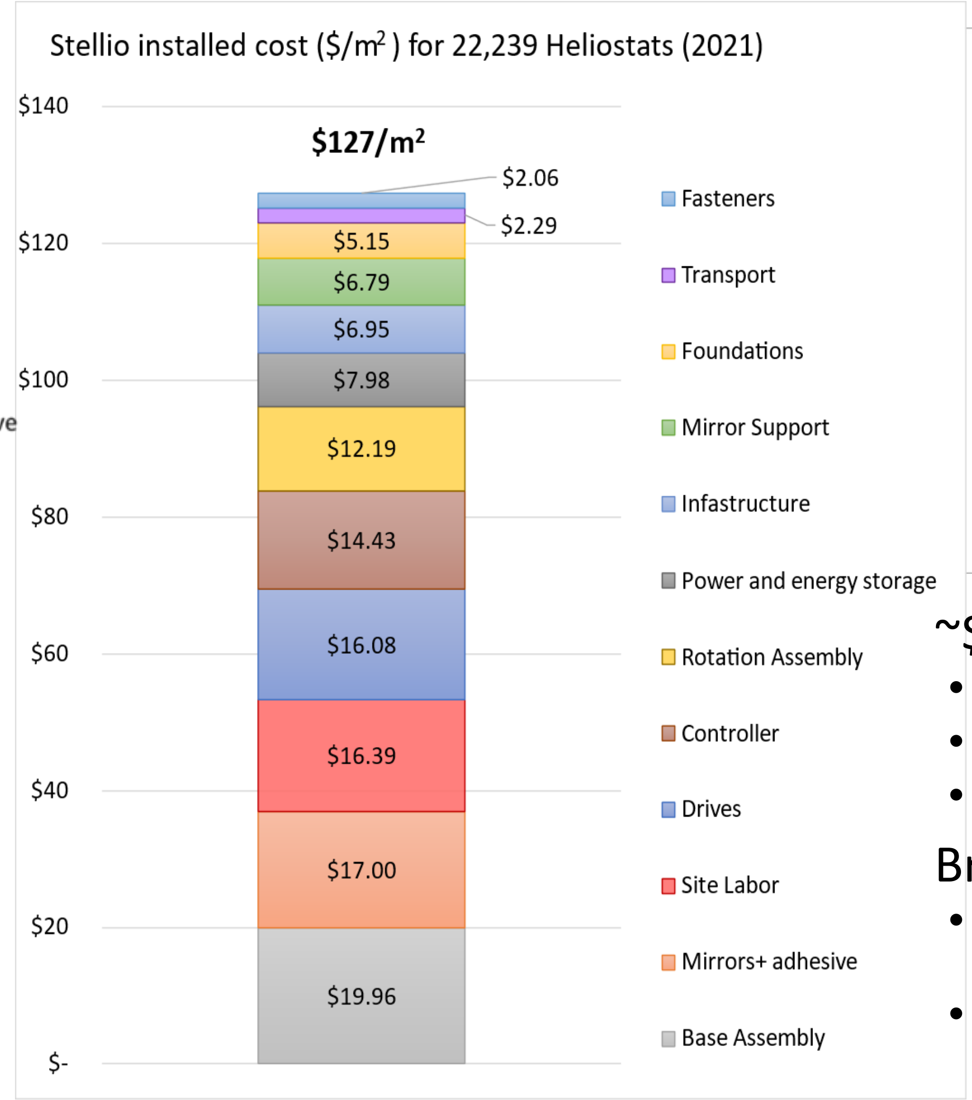


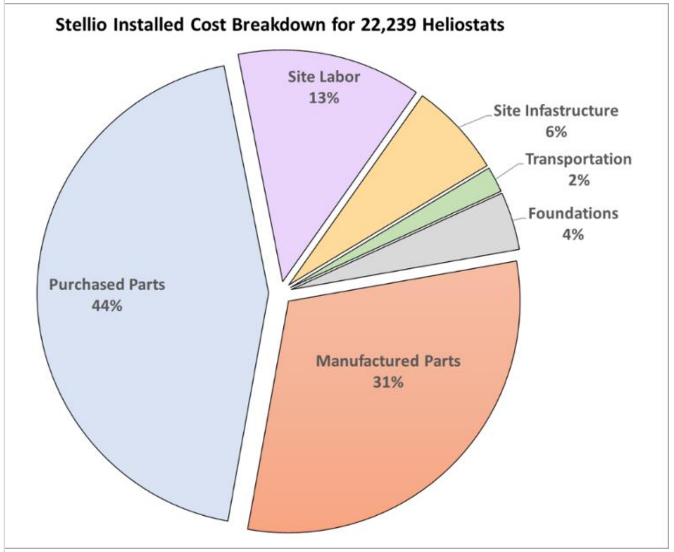
sbp Stellio Bottom-Up Analysis



Reflective area of ~48.5 m^2

Assumed solar field with 22,239 heliostats represents 1,067,472 m^2 of total aperture area





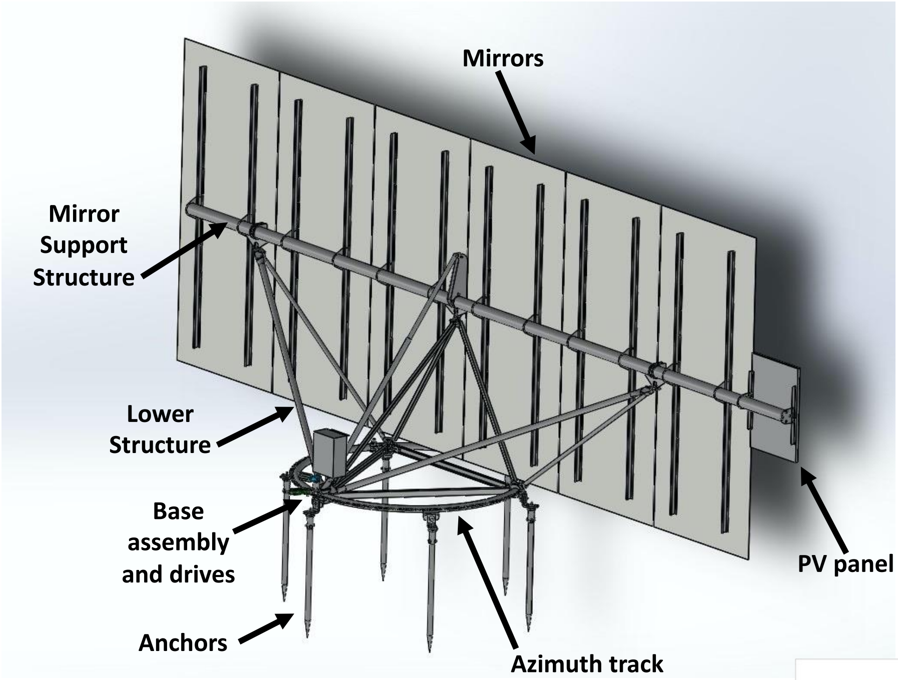
~$127/m^2 installed cost (±10%)

- ~$7.5M assembly facility
- Base assembly (15.7%)
- Mirrors (13.4%)

Breakdown by category

- 44% purchased components (e.g., rivets, mirrors, drives)
- 31% manufactured parts (e.g., arms, frame…)

Solar Dynamics Drop-C Ring Bottom-Up Analysis



~$99/m2 installed cost (±5%)

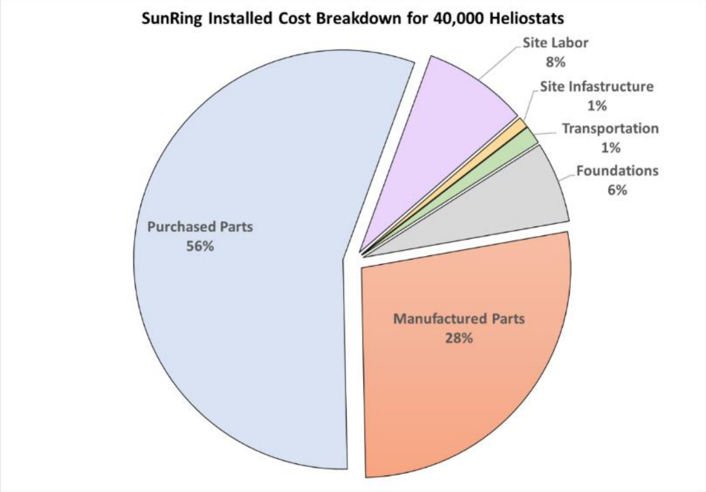
- ~$0.85M assembly facility
- Drives (16.6%)
- Mirrors (16.0%)

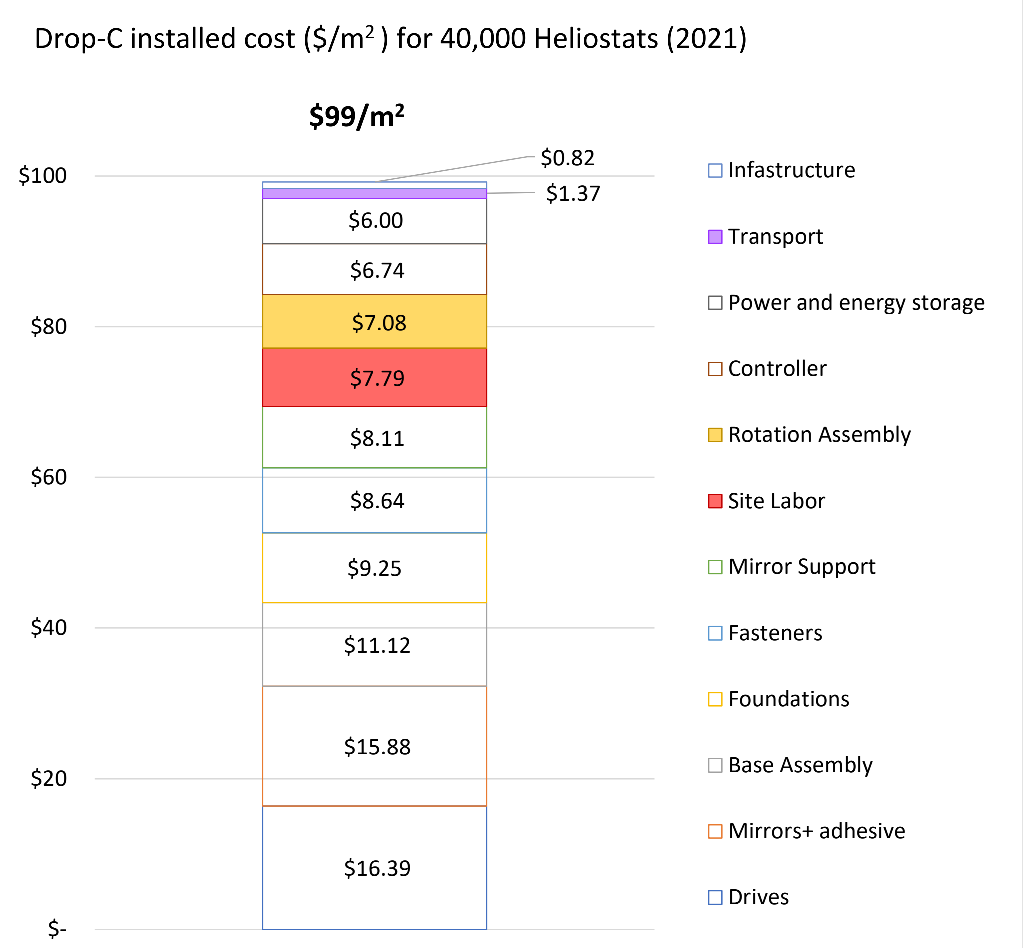
Breakdown by category

- 54% purchased components (e.g., rivets, mirrors, drives)
- 27% manufactured parts (e.g., frame…)

Reflective area of ~26.9 m^2

Assumed solar field with 40,000 heliostats represents 1,078,560 m^2 of total aperture area





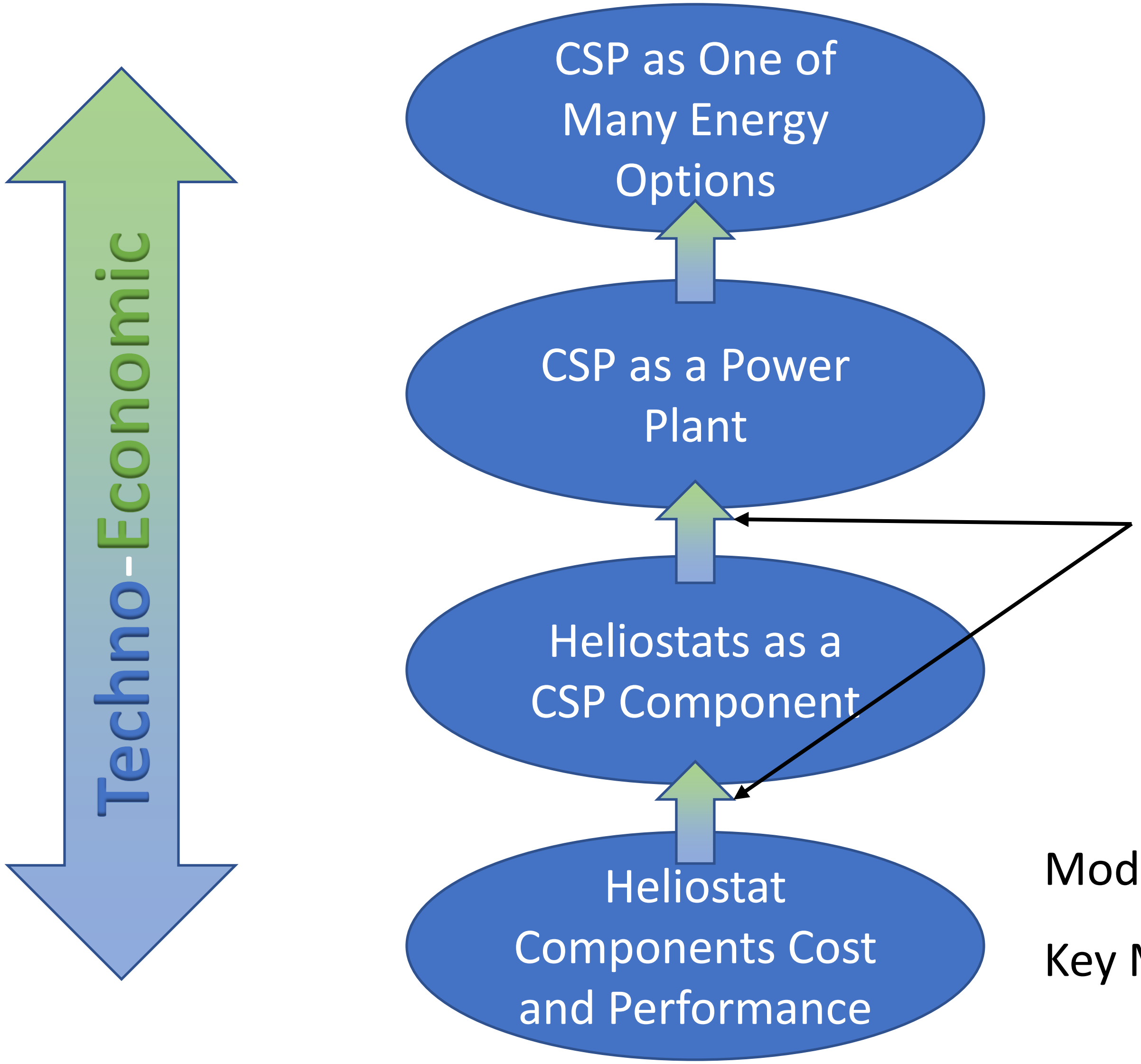
SBP Stellio Heliostat – Example of Detail

- Fixturing costs associated with welding the subassemblies and manufacturing jigs, (not including the equipment investment), is approximately $300,000.
- SBP Stellio heliostat assembly process requires
  - 16 person hours per heliostat
  - 5 person hours for the rest of tasks for Pylon installation
- Capital cost for the assembly building, assembly lines, overhead cranes, and rest of equipment such like trolleys, heliostat transportation platforms are based upon the months available for the solar field execution:
  - For 21 months execution = 1 Assembly Lines, CAPEX required of $7.5M
  - For 15 months execution = 2 Assembly Lines, CAPEX required of $10.5M

Share of raw material cost and manufacturing cost (including coating) with respect to total cost of main components based on SBP`s cost estimates.

Main Component	Raw Material Cost vs Total Cost	Manufacturing Cost + Coating vs Total Cost
Purlins	63%	37%
Cantilever Arms	45%	55%
Boomerang	53%	47%
Central Hub	56%	44%
Pylon Head	49%	51%

CSP Technoeconomic Analysis



Top-Down Analysis

- How much do the inputs matter?
  - Error range
  - Parametric Analysis
  - Monte Carlo simulations
  - Tornado Plots
  - Screening
- Role of Topic 8 TEA in HelioCon

Model Types: Component-specific (mirror, base)

Key Metrics: Unit Cost
Unit Performance Metrics

HelioCon: Technoeconomic Analysis

Topic Objectives:

1. Develop baseline heliostat field and benchmark existing heliostat/CSP costs
2. Assess R&D ideas from other topics for potential CSP cost reductions (i.e., is it worth studying?)
3. Develop TEA tools to aid HelioCon and CSP industry

Team Members: Kenneth Armijo, Sandia (Co-Lead)
Alexander Zolar (NREL)

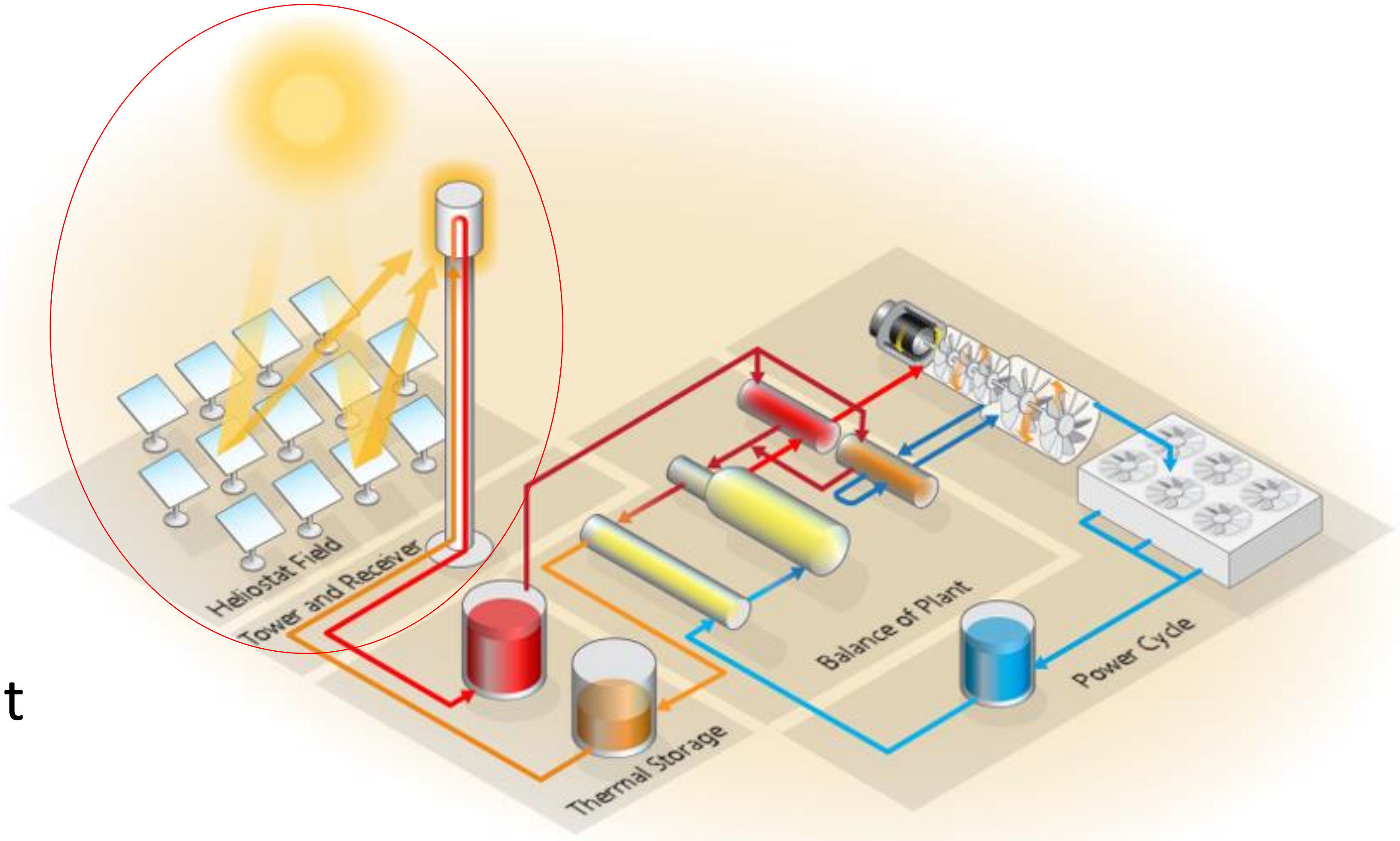
Background and Context

- The TEA topic assumes that other topics will need (us) to model solar fields to fill in knowledge gaps and determine the cost/benefit ratio of their research efforts
- We want to have HelioCon analysis across topics to be done on a consistent “apples-to-apples” comparison as much as possible
- To achieve this, we shall develop a set of base case heliostat fields to be used in HelioCon analysis
    - The base cases should span the reasonable use cases for heliostat fields in the present and future

TEA Models Scope

<u>Heliostat Field + Receiver</u>

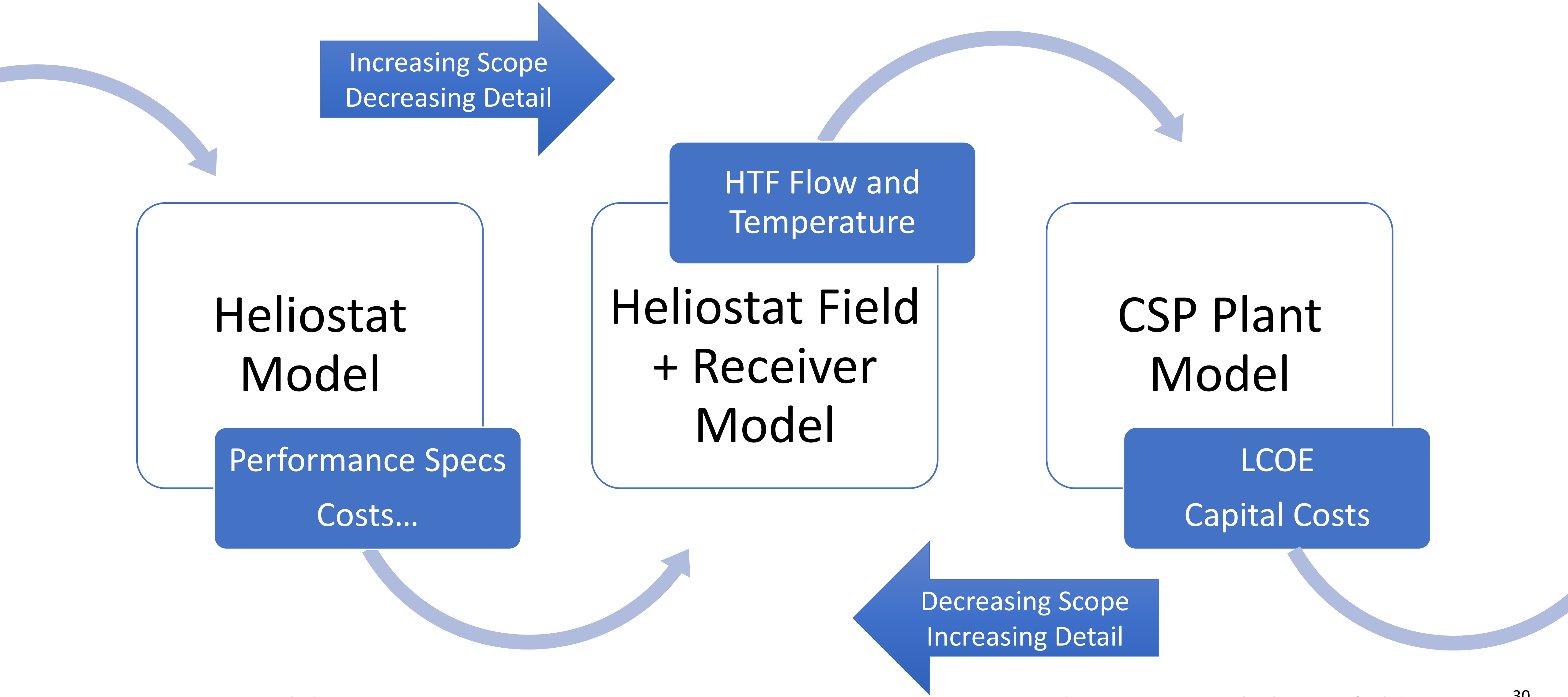
- Aiming and ray-tracing models
- Heliostat performance
- Heliostat + Receiver interaction
- Determines thermal energy input to plant (**Levelized Cost of Heat – LCOH**)



SAM has five main “levers” for exploring heliostat field cost and performance

1. Installed heliostat cost ($\$/m^2$)
2. Reflected image error (mrad)
3. Reflectance (%)
4. Field O&M cost ($\$/m^2/year$)
5. Construction time (months)

TEA Model Systems View



conceptual design • components • integration • mass production • heliostat field

SAM has five main “levers” for exploring heliostat field cost and performance

Reflected Image Error (mrad)

- Slope error
- Pointing error
- Reflected beam error
- Error from wind load…

Installed Cost ($/m²)

- Heliostat design
- Material cost
- Manufacturing cost
- Assembly cost
- Installation cost…

Reflectance (%)

- Material
- Degradation
- Soling rate
- Washing schedule…

Field O&M Cost ($/m²/year)

- Washing schedule
- Design (height)
- Repairs and replacements…

Construction Time (months)

- Field installation time
- # of assembly buildings
- Tower install time
- Heliostat calibration…

Baseline #1: Electrici[illegible]n – Large Solar Field

Preliminary!

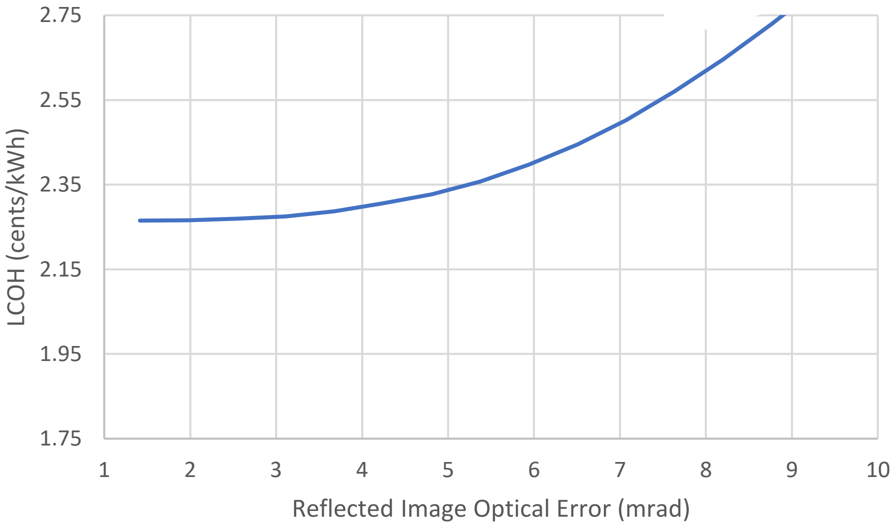
Use Case – single surround field around central external receiver to supply thermal energy to thermal power plant

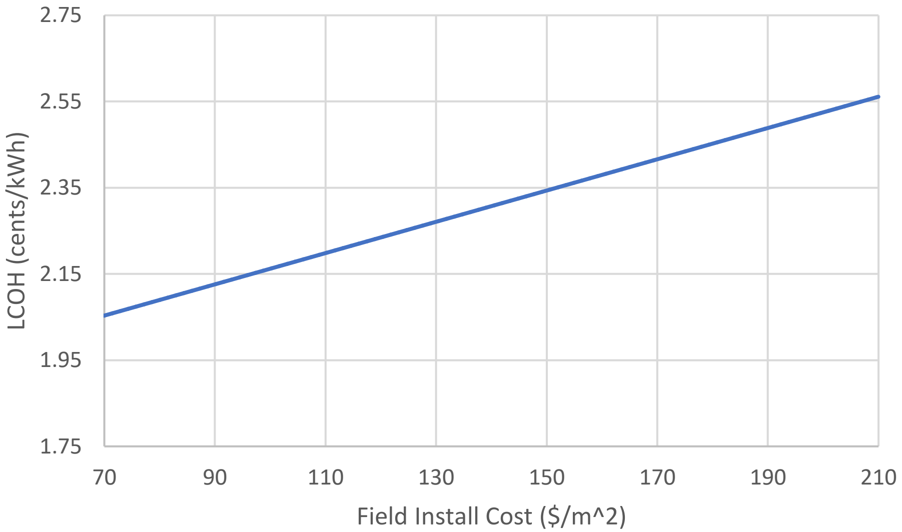
- SAM molten salt power tower default case can serve as base case
  - Net Power Output: 100 MW_e/727 MW_{th}
  - Surround Heliostat Field
    - Solar Multiple: 2.7
  - External Receiver
    - Solar Salt (60% $NaNO_3$/40% KNO_3)
      - Max heat flux – 1 MW/m2
    - Hot Side Temp: 575°C
    - Cold Side Temp: 290°C

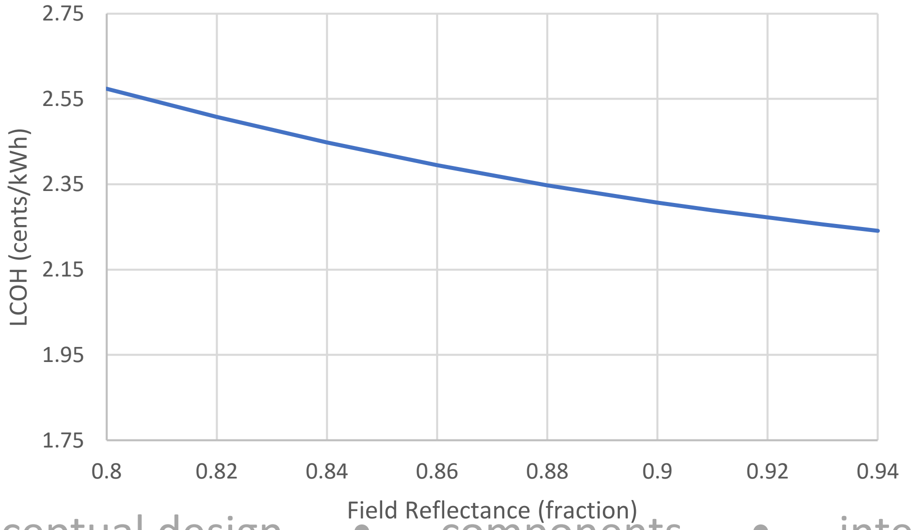
1. Installation cost: \$140/m^2
2. Reflected image optical error: 4.3 mrad
3. Reflectance (includes soiling): 90%
4. Field O&M cost:
   - Still need to break out field O&M from plant O&M
   - Includes availability
5. Construction time: 24 months

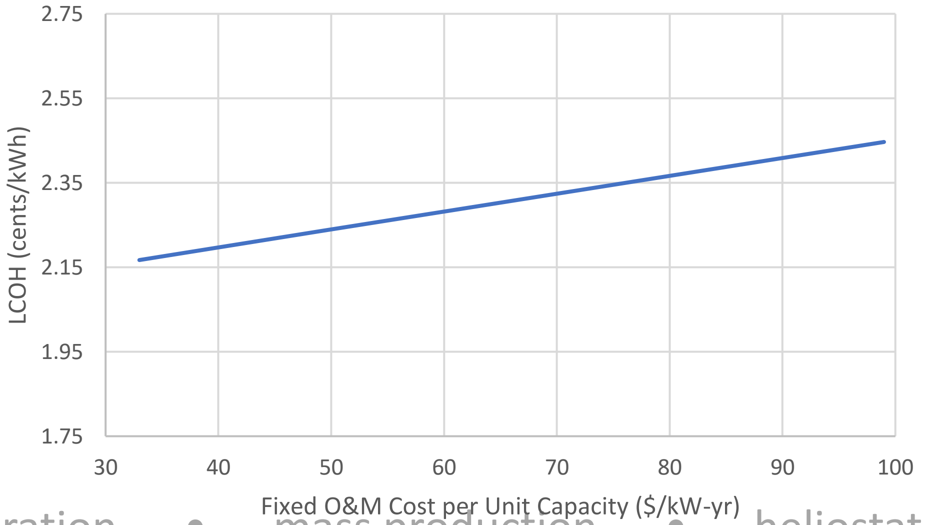
LCOH Parametric An… …ectrical Field

Preliminary!



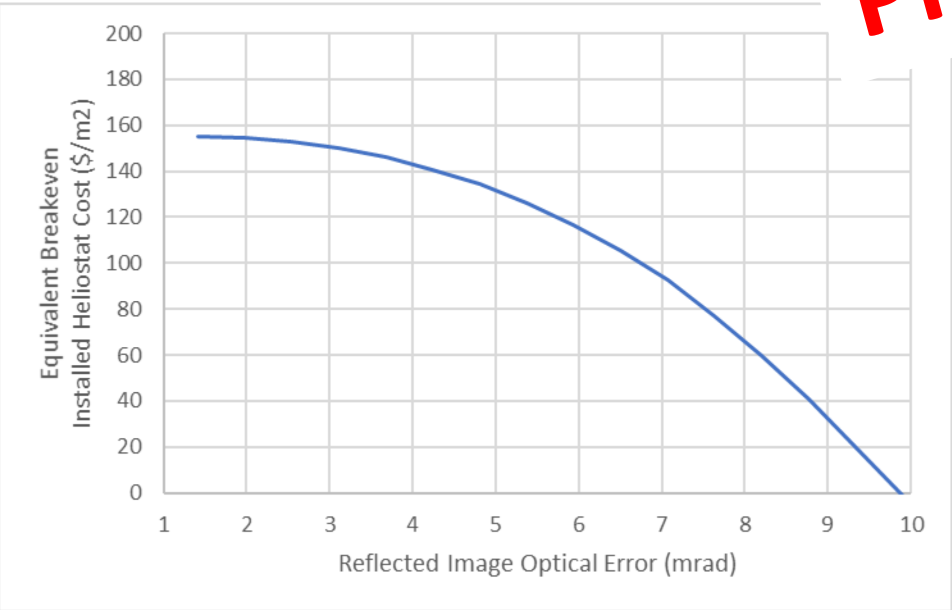


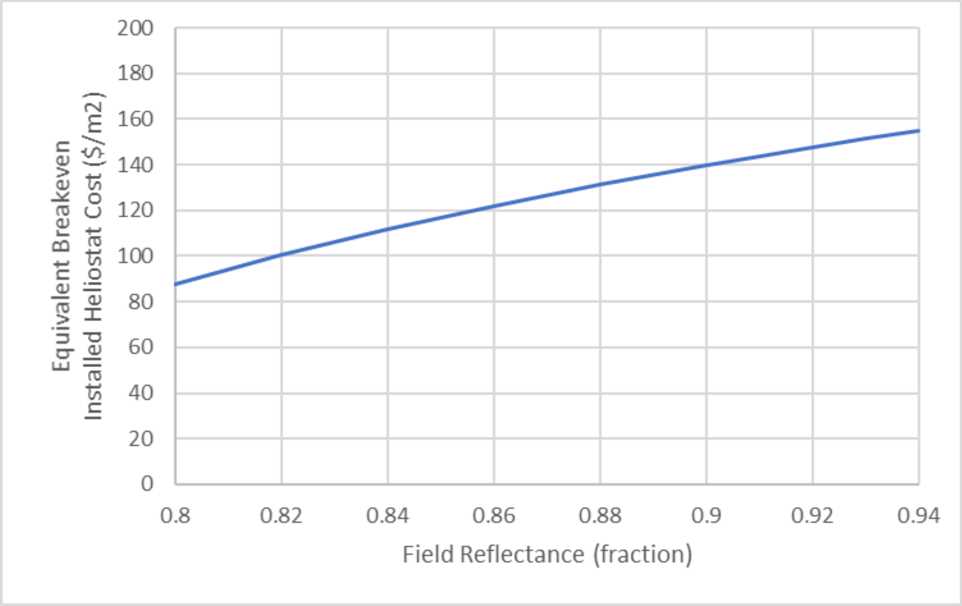


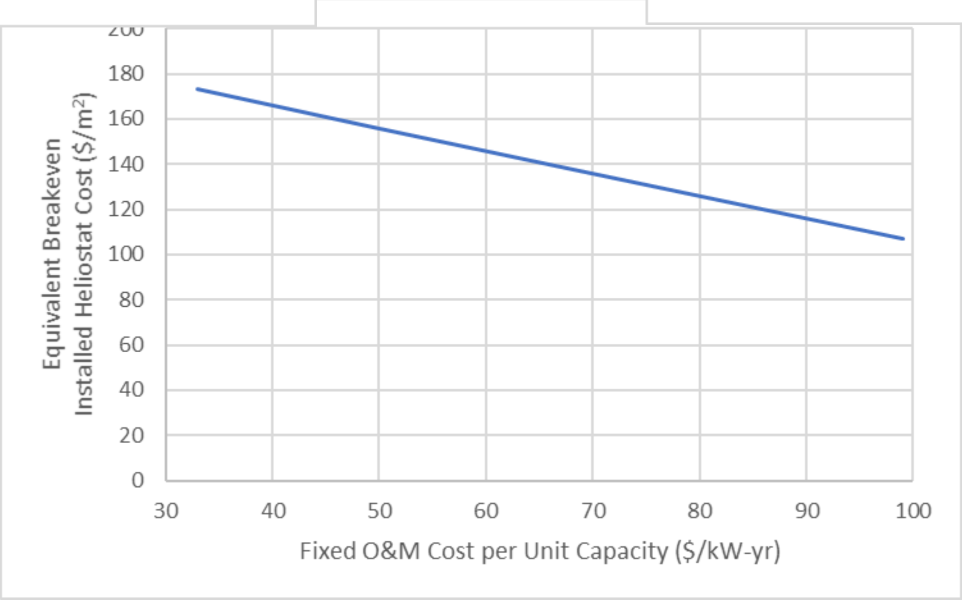


LCOH – Equivalent B… …liostat Cost

Preliminary!



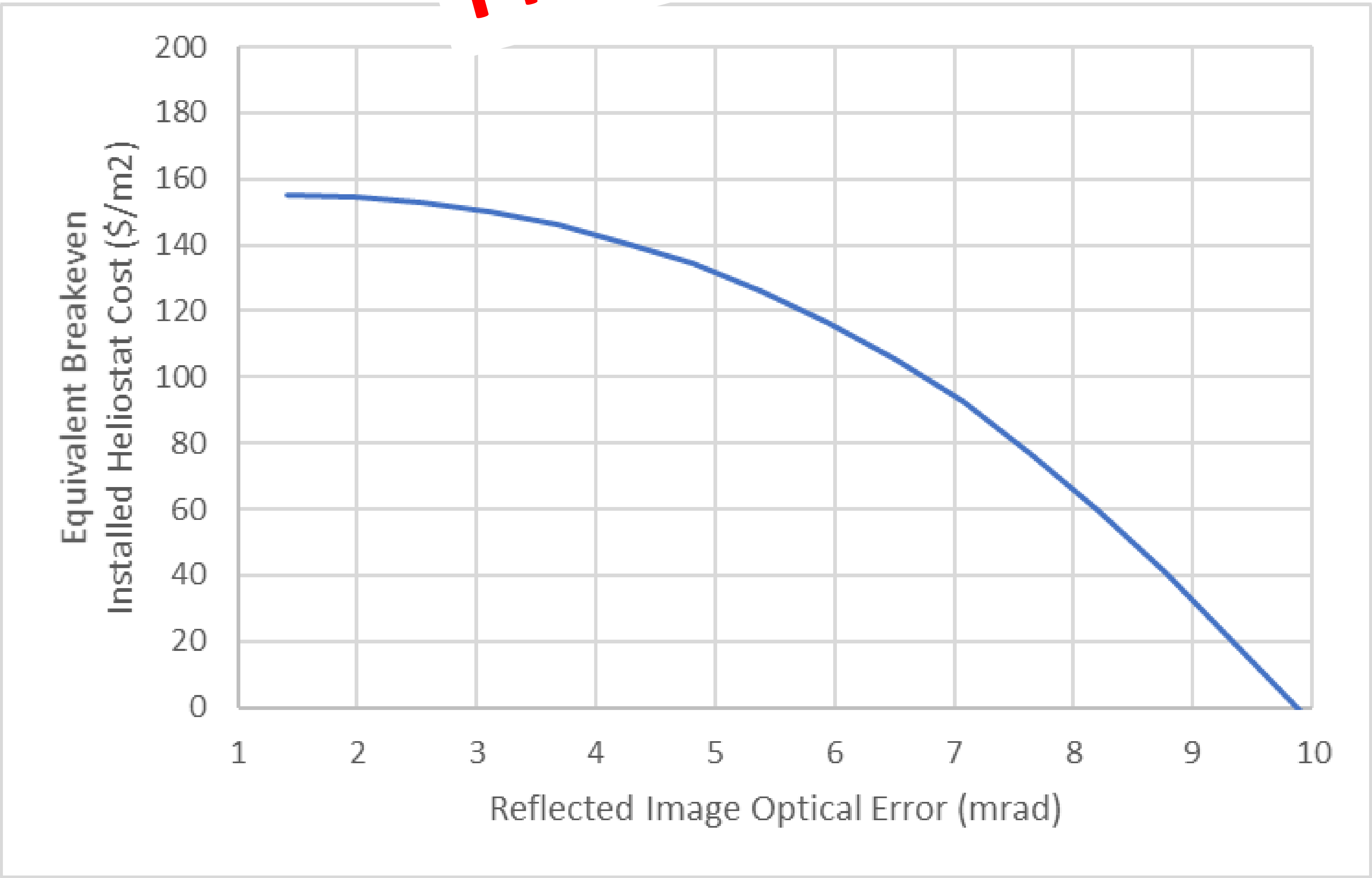




Equivalent Breakeven Installed Capital Cost:
Cost of the heliostat that would offset the observed change in LCOE

LCOH – Equivalent B… ostat Cost

Preliminary!



Baseline #2: Electric[illegible] – Modular Field

Preliminary!

Use Case – single polar field with cavity receiver to supply thermal energy to large thermal power plant fed by one or multiple fields (doesn't matter for base case since we stop at tower/receiver)

- Molten salt power tower
  - Net Equivalent Power Output: 30 MW_e/220 MW_{th}
  - Polar Heliostat Field
    - Solar Multiple: 2.7
  - Cavity Receiver
    - Solar Salt (60% $NaNO_3$/40% KNO_3)
    - Hot Side Temp: 575°C
    - Cold Side Temp: 290°C
    - Assume this is more efficient (and cost effective) than an external receiver

1. Installation cost: \$145/m^2
2. Reflected image optical error: 4.3 mrad
3. Reflectance (includes soiling): 90%
4. Field O&M cost: need to break out field O&M from plant O&M
   - Includes availability
5. Construction time: 12 months (?)

Baseline #3: Industri… …at – Small Field

Preliminary!

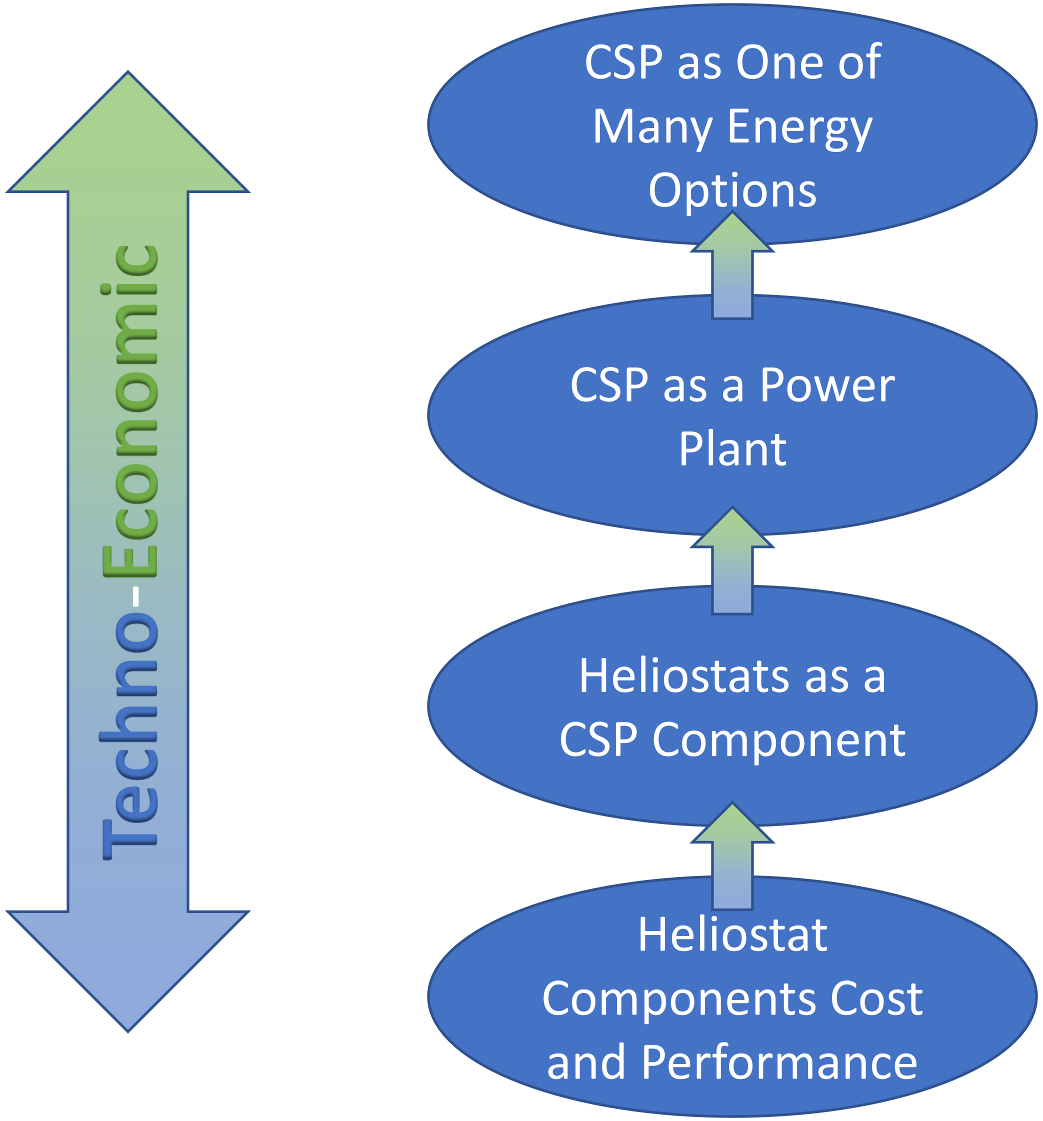
Use Case – single polar field with cavity receiver to supply thermal energy for high-temperature industrial process (ex. - calcination of limestone)

- Molten salt power tower
  - Net Equivalent Power Output: 10 MWth
    - 1.5 MWe equivalent
    - Needs work – what is concentration ratio limit?
  - Polar Heliostat Field
    - Solar Multiple: 1.0 (assume no storage)
  - Cavity Receiver
    - Temp: 1,000 °C (continuous process)
    - Receiver is the reactor

1. Installation cost: $\$145/m^2$
2. Reflected image optical error: 4.3 mrad
3. Reflectance (includes soiling): 90%
4. Field O&M cost: need to break out field O&M from plant O&M
   - Includes availability
5. Construction time: 12 months

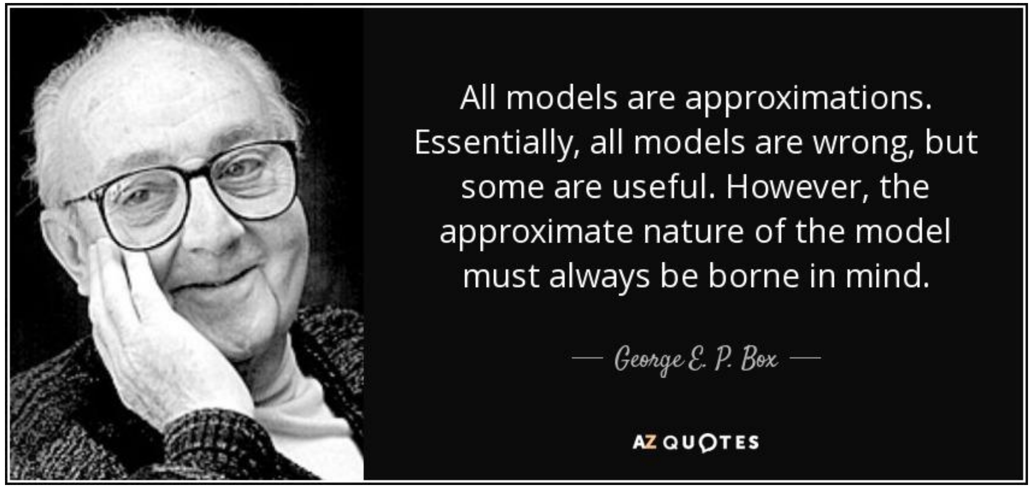
Note how for the SAM inputs, the values don't differ among base cases, except for construction time. Analysis should reveal relative importance of parameters to solar field for each base case

Summary – CSP Technoeconomic Analysis



TEA Goals

- Develop Baseline cases
- Consistent assumptions across topics
- Identify and quantify opportunities
- Develop useful tools and models to HelioCon



Questions?
Thank you!

www.nrel.gov

chad.augustine@nrel.gov

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HelioCon Seminar Series: An Undervalued Foundation for Heliostat Technologies – Optical Characterization, Modeling, and Measurement

Speaker: Guangdong Zhu, NREL

When: 1-2pm Wednesday February 16th

Zoom:https://nrel.zoomgov.com/j/1611110823?pwd=Z0NQTlVmZ2NhSXZmbnIwNnhRZWNWQT09