SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Optimizing the Supercritical CO2 Brayton Cycle for Concentrating Solar Power Application

The 6th International Supercritical CO2 Power Cycles Symposium
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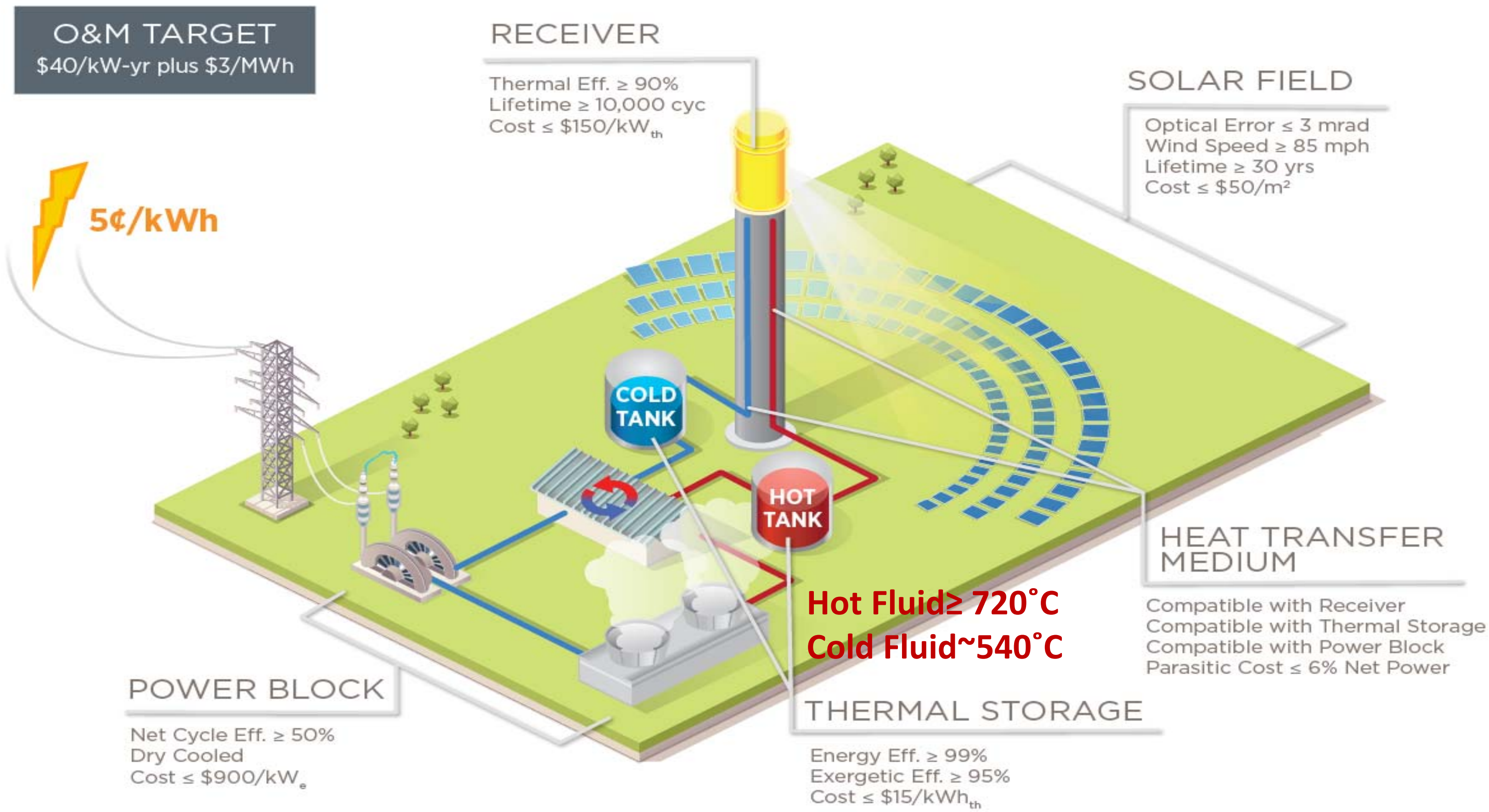
Talk Objectives

- Rapid Introduction to Concentrated Solar Power (CSP), with Focus on SETO Goals
- sCO_2 techno-economics aligned with cost competitive CSP, with focus on the Following:
  - power block efficiency
  - power block cost
  - primary heater temperature change (ΔT)
  - CSP HTM-to-sCO_2 heat exchanger
  - dry cooling
  - Operation and maintenance (O&M), including consideration of autonomous CSP power cycle operation
- For each Area, Solar Energies Technology Office-Funded sCO_2 Research Quick review
- For each Focus Area, Provide overview of technology development needs for future sCO_2 research aligned with CSP Requirements


O&M TARGET
$40/kW-yr plus $3/MWh
5¢/kWh
RECEIVER
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cyc
Cost ≤ $150/kW$_{th}$
SOLAR FIELD
Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
Cost ≤ $50/m²
COLD TANK
HOT TANK
HEAT TRANSFER MEDIUM
Compatible with Receiver
Compatible with Thermal Storage
Compatible with Power Block
Parasitic Cost ≤ 6% Net Power
Hot Fluid≥ 720˚C
Cold Fluid~540˚C
POWER BLOCK
Net Cycle Eff. ≥ 50%
Dry Cooled
Cost ≤ $900/kW$_{e}$
THERMAL STORAGE
Energy Eff. ≥ 99%
Exergetic Eff. ≥ 95%
Cost ≤ $15/kWh$_{th}$

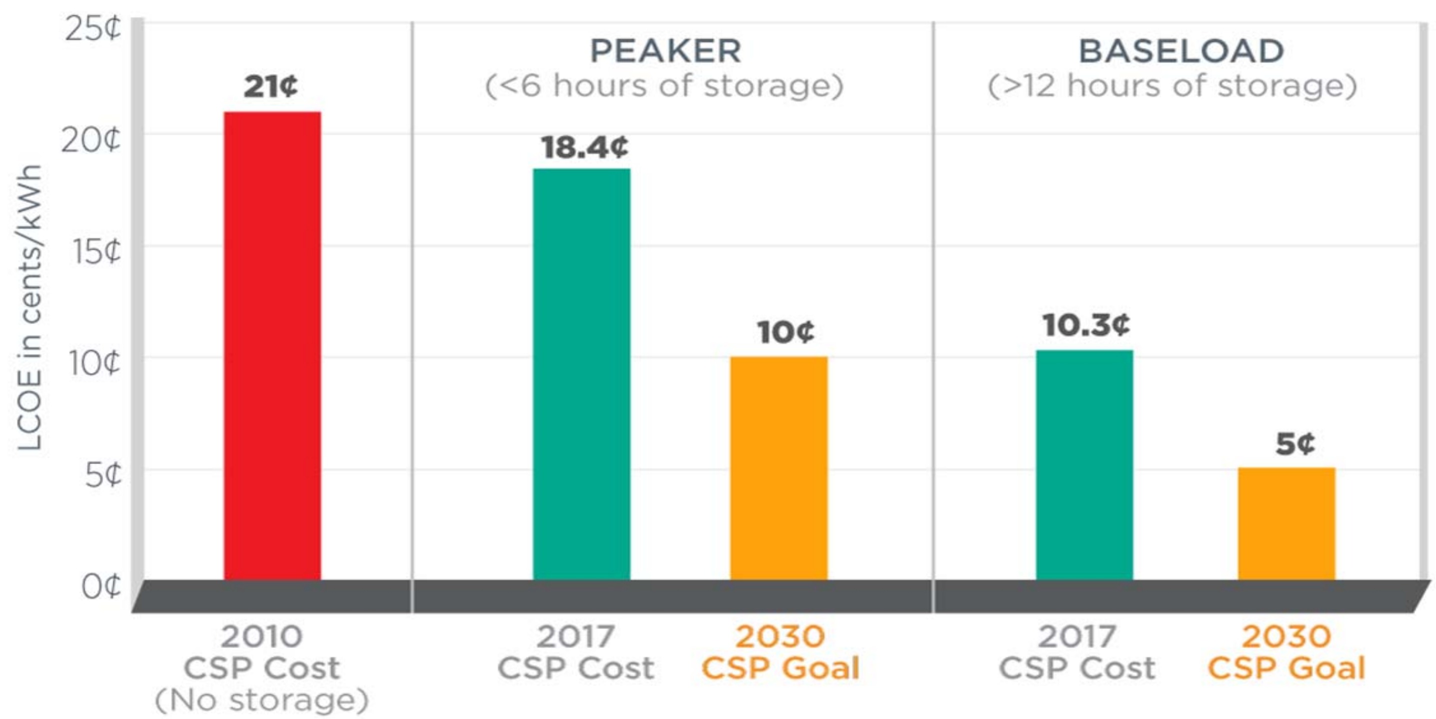
Technology Development Pathways for Gen3 CSP

COLLECTOR FIELD	RECEIVER	THERMAL TRANSPORT	THERMAL STORAGE	HEAT TRANSFER MEDIA	HEAT EXCHANGE	POWER CYCLE
SOLID MEDIA	• Thermal Efficiency: • Particle Loss • Flow Velocity Control and Monitoring	• Reliability • Mechanical and Thermal Efficiency • Scalability • Insulation	• Charging and Discharging Particle loss, Efficiency, Scalability	• Particle Attrition • Optimized Performance Character	• Low Cycle Fatigue • Particle Mass Flow Control • Ramp Rates & Transients	
MOLTEN SALT	• Thermal Conductivity • Thermal Stability • Tube Strength and Durability	• Pipe Material Compatibility • Freeze Recovery • Pumps Valves Seals • Leak Detect	• Corrosion Behavior • Chemistry Monitoring and control • Tank Cost	• Characterize Material Properties • Cost / Supply Chain	• Material Compatibility w/ salt & CO_2 • Freeze Protection • Thermal Ramp Rates	
GAS	• High Pressure Fatigue • Absorptivity Control and Thermal Loss Management	• Recirculator Cost & Operating Power • Large Pipes High Cost	• Storage Concept not Determined	• Low Thermal Conductivity • Low Heat Capacity	• Requires High Area • Multiple Heat Exchangers • Cascading Temperature	

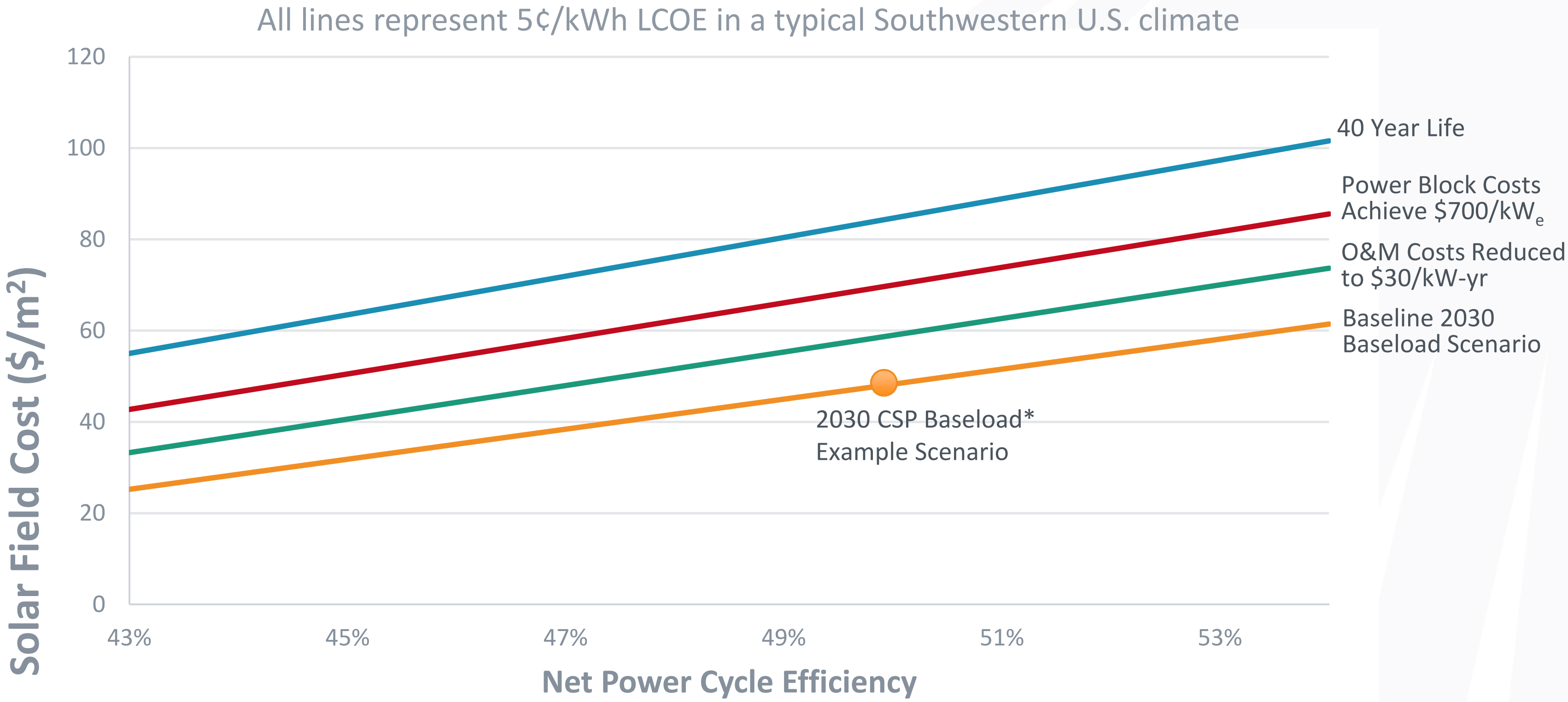
SETO sCO_2 Power Cycle Portfolio by Category

CATEGORY	PROJECT TITLE	PRIME
Turbomachinery	Compression System Design and Testing for sCO_2 CSP Operation	GE
	Development of an Integrally-Geared sCO_2 Compander	SwRI
	Development of High Efficiency Expander and 1 MW Test Loop	SwRI
	Physics-Based Reliability Models for sc-CO_2 Turbomachinery Components	GE
Materials	Lifetime Model Development for Supercritical CO_2 CSP Systems	ORNL
	sCO_2 Corrosion and Compatibility with Materials	UW-Madison
Components	Development and Testing of a Switched-Bed Regenerator	UW-Madison
	sCO_2 Power Cycle with Integrated Thermochemical Energy Storage	Echogen Power Systems
Technoeconomics	Cycle Modeling, Integration with CSP, and Technoeconomics	NREL
Primary Heat Exchanger	High Flux Microchannel Direct sCO_2 Receiver	Oregon State
	High-Temperature Particle Heat Exchanger for sCO_2 Power Cycles	SNL
	Robust, Cost-Effective Molten Salt HXer for 800°C Operation with sCO_2	Purdue
	Solar Receiver with Integrated Thermal Storage for sCO_2	Brayton Energy

2030 CSP Levelized Cost of Electricity Targets



Pathways to Achieving SunShot 2030 Goals

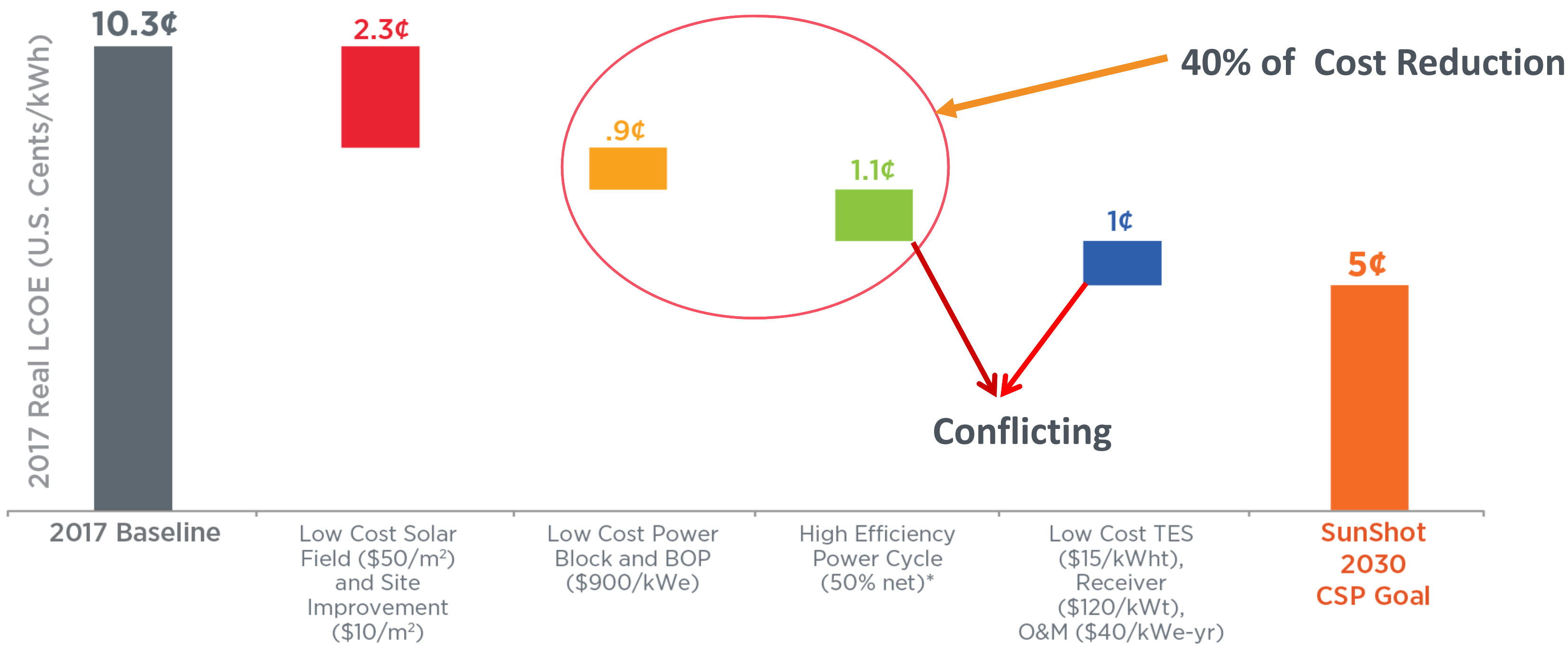


*Baseload power plant is defined as a CSP plant with greater than or equal to 12 hours of storage

sCO_2 Cycle Technology Improvement Focus Areas

- Power block efficiency
- Power block cost
- Primary Heater Temperature Change (ΔT)
- CSP Heat Transfer Fluid-to-sCO_2 heat exchanger
- Dry cooling
- Operation and Maintenance (including consideration of autonomous CSP power cycle operation)

Power Block Cost Improvements: Background

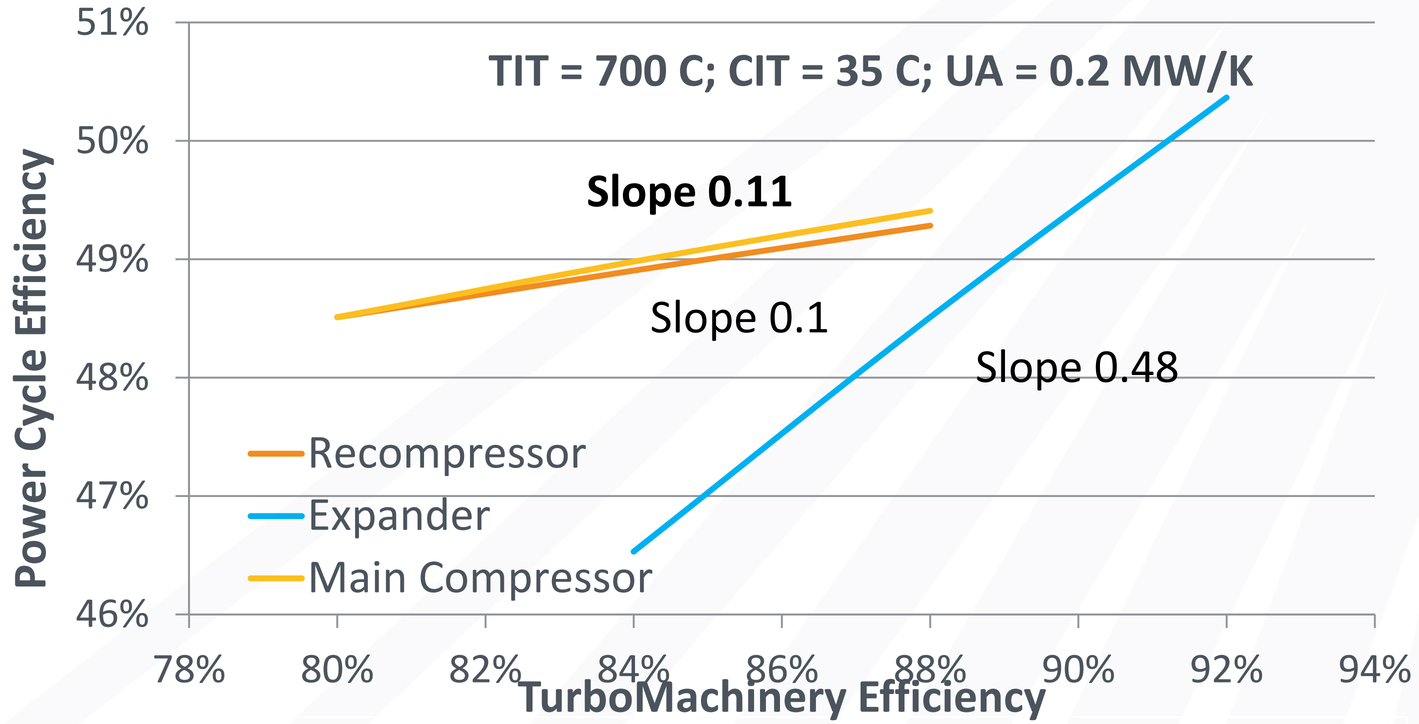


*Assumes a gross to net conversion factor of 0.9

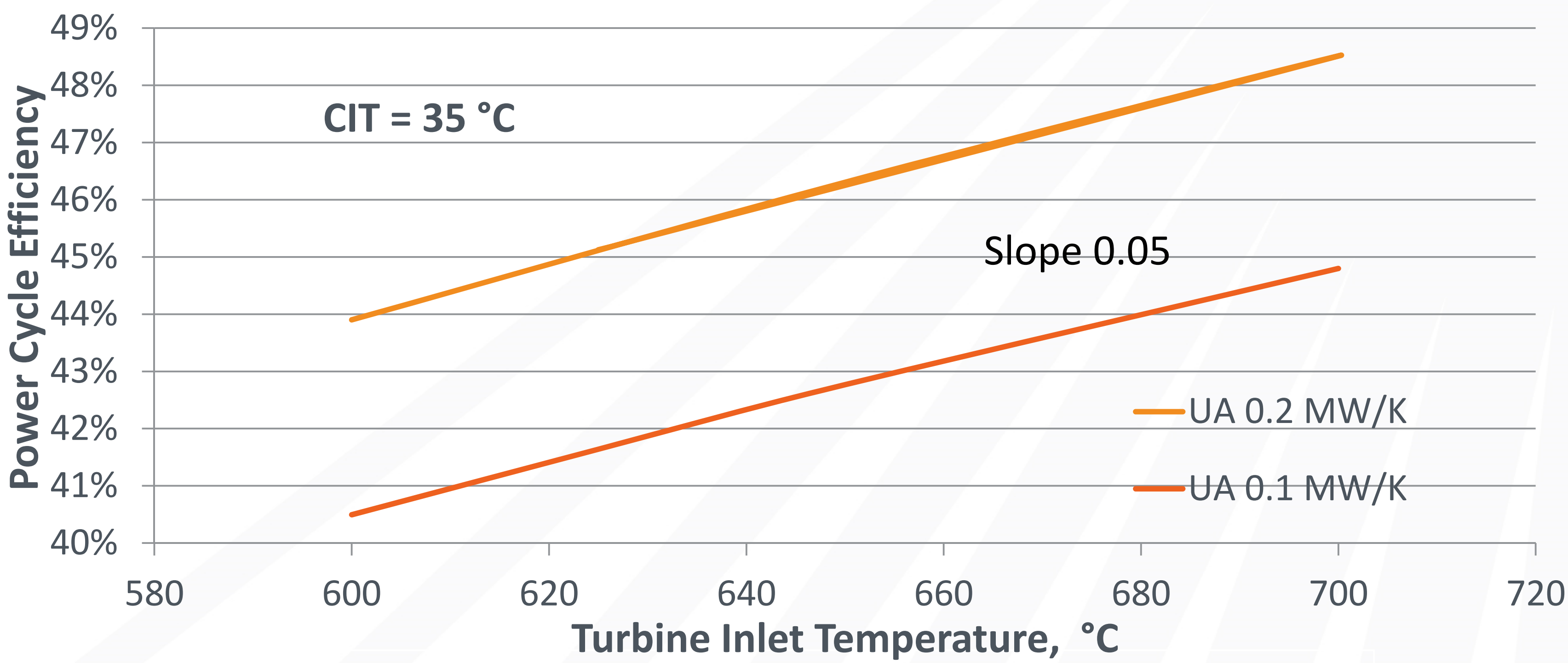
Review of Solar Energy Technologies Office sCO_2 Portfolio: Power Block Efficiency

Turbomachinery			
2012 SunShot	2013 Predicts	2015 Apollo	2015 Apollo
Turboexpander	Bearings / Seals	Compander	Compressor
Heat Exchangers	**Corrosion**		**Technoeconomics**
2015 Apollo	2015 SunLamp	Various Awards	2015 SunLamp
Regenerator			Sys. Advisory Model

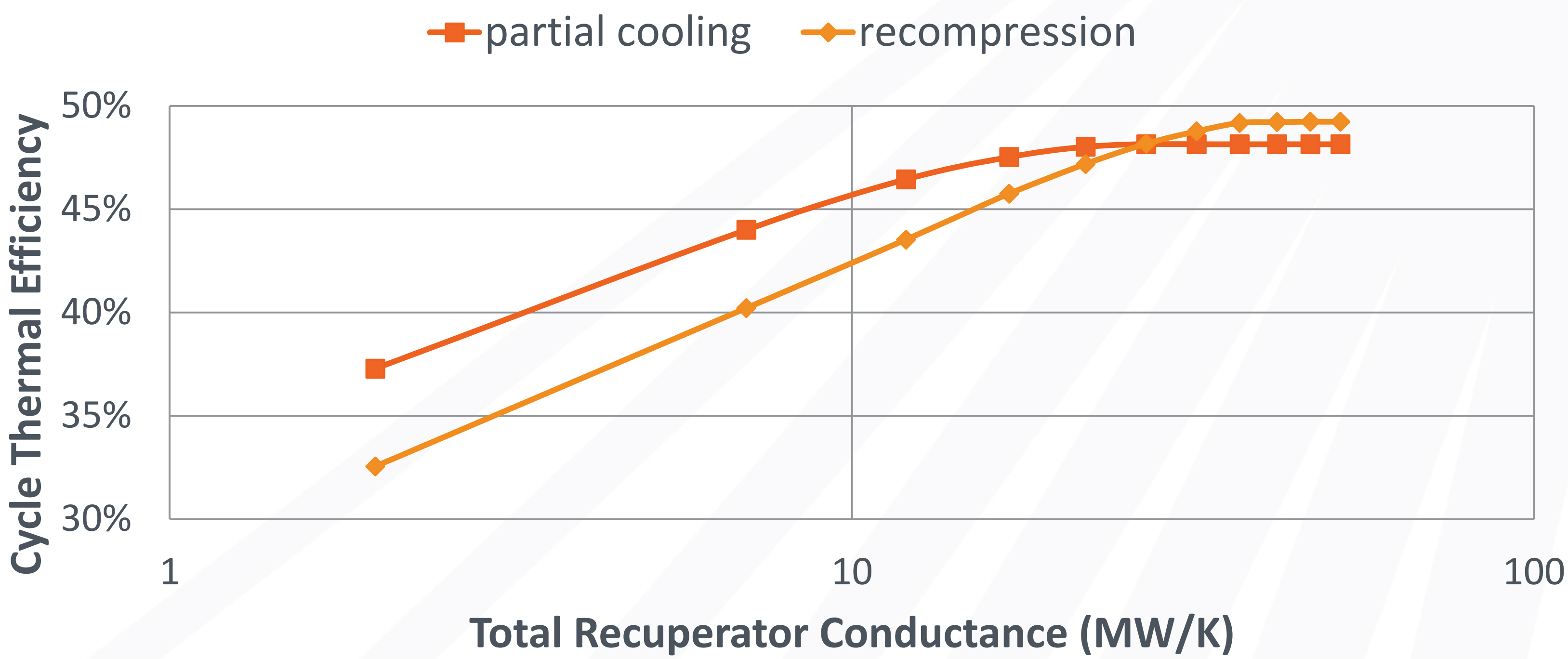
Power Cycle Efficiency Improvements: Background



Power Cycle Efficiency Improvements: Background



Power Cycle Efficiency Improvements: Background



Near Term sCO_2 Component Innovations: Power Cycle Efficiency

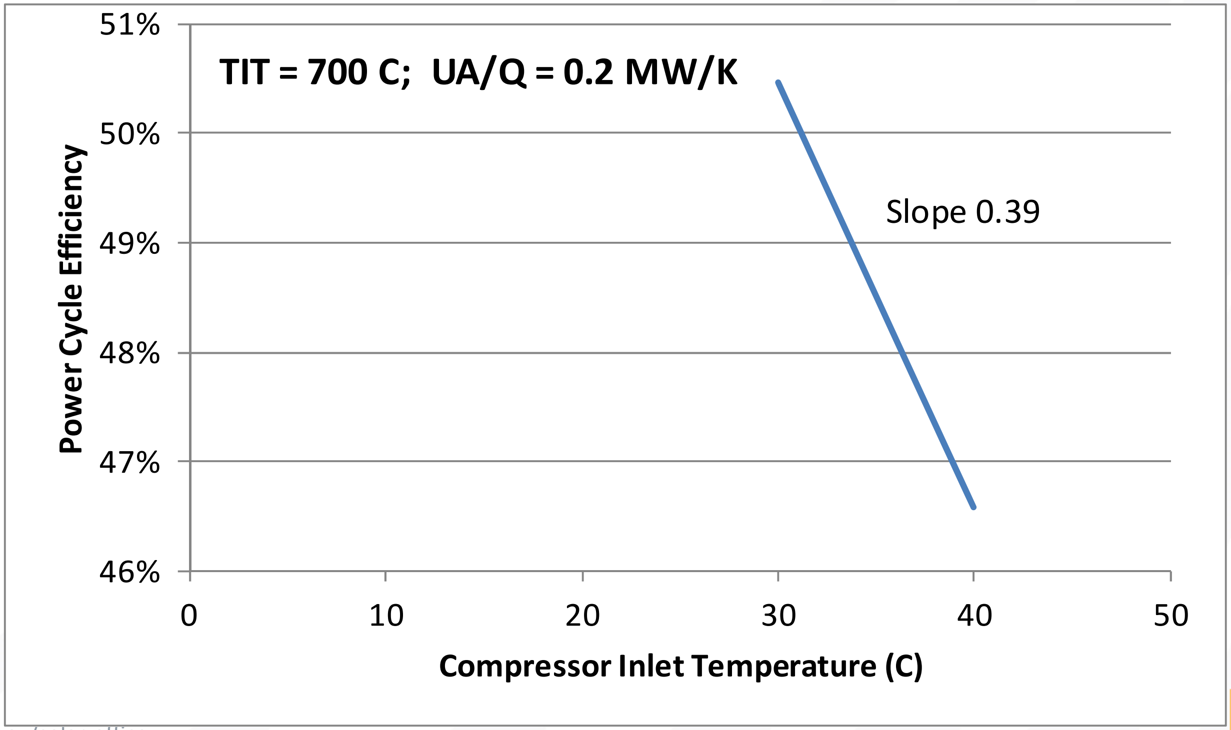
- Component Innovations Supporting Cycle Efficiency Improvements Advantageous to CSP
  - Compressor and Turbine Efficiency Improvements that can lead to higher (50%) Efficiency, possibly at Lower Turbine Inlet Temperatures (≤650 °C)
  - Noticing the Levelling of Cycle Efficiency with Increase in UA, and Difficulties in Extending the Effectiveness of Compact Heat Exchangers Beyond 92%, Seek Alternate Recuperators Such as Valved Solid Bed Regenerators; Lower Cost per kWth and Higher Effectiveness, with Accompanying Cycling issues
  - Packaging of Compressors and Turbines into Inline Single Housing Can Reduce Expander Leakage, and Reducing the number of Seals and Bearings
  - Optimization of Expander efficiency by careful consideration of Stages, Sealing and Turbomachinery Design

Long Term sCO_2 Component Innovations: Power Cycle Efficiency

- Component Innovations Supporting Cycle Efficiency Improvements Advantageous to CSP
  - Focusing on Compressors (Close to 30% of Turbine Power Expended in Compression)
    - Liquid Inlet Conditions Possible in Southwest USA when Nigh Temperature Drops Well Below Critical Point; Wet Gas Compression as Topic of Further research
    - Isothermal Compression for sCO_2
  - Further Efficiency Improvements for Large (≥100 Mwe) Machines using Axial Flow Compressors
  - Compressor Inlet Temperature Control Using Heat Rejected from cycle and Heat Pumps

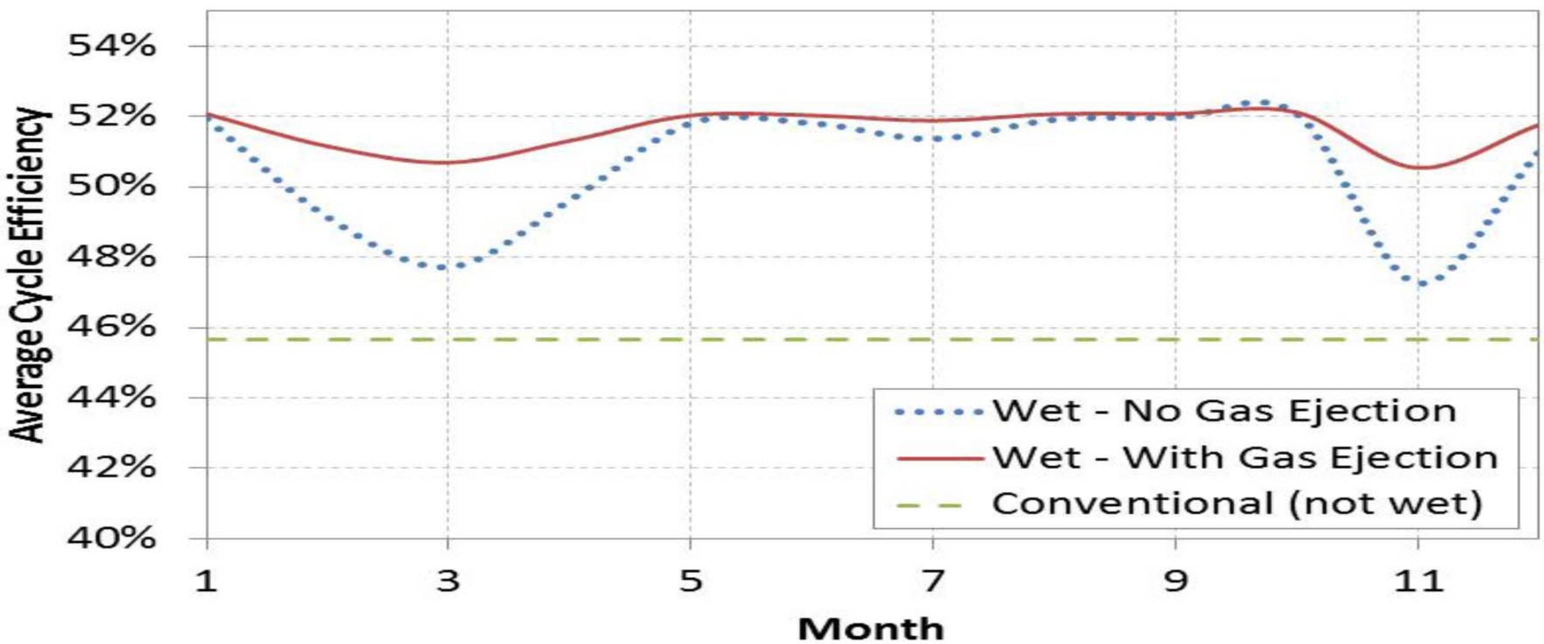
Long Term Compressor Development Needs for CSP

- Move Design Basis for Compressor Inlet Temperature Close to 31 C, with Wide Range Inlet Conditions



Long Term Compressor Development Needs for CSP

- Move Design Basis for Compressor Inlet Pressure Close to 73.8 Bars
  - Wet Gas Compression Can Improve Cycle Efficiency by Several Points[1]



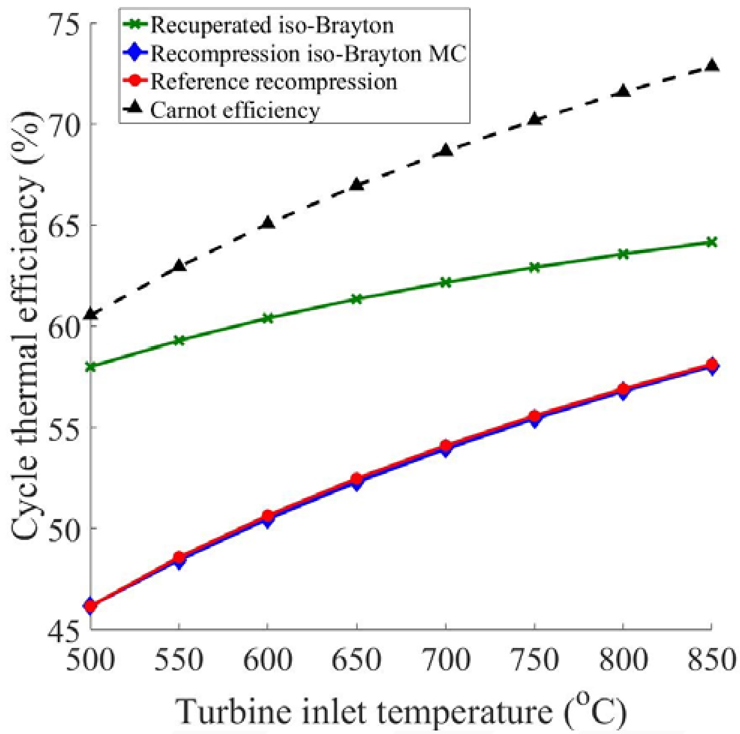
M Poerner, G Beck, G Musgrove, C Nolen. UNDERSTANDING WET GAS COMPRESSION IN A SUPERCRITICAL CARBON DIOXIDE CYCLE. *The 5th International Symposium - Supercritical CO2 Power Cycles, March 28-31, 2016, San Antonio, Texas*, 2016

Low TRL Compressor Technologies

- Move Design Basis for Compressor Inlet Temperature Close to 31 C/73.8 Bars
  - Liquid Volume Fraction and Liquid Mass Fraction Large at sCO_2 Critical Point; No Practical Experience with wet sCO_2; low TRL Technology
  - Design Compressors that Can Handle >20% LVF and LMF
  - Handle Interactions between Liquid Droplets and IGVs and Other Means of Range Extension

Low TRL Compressor Technologies

- Quasi-Isothermal Compression; no Design Experience in sCO_2; IsoCompression Brayton Cycles Can Increase Power Cycle Efficiency[1] GT2017-63322, "A STUDY OF S-CO2 POWER CYCLE FOR CSP APPLICATIONS USING AN ISOTHERMAL COMPRESSOR"



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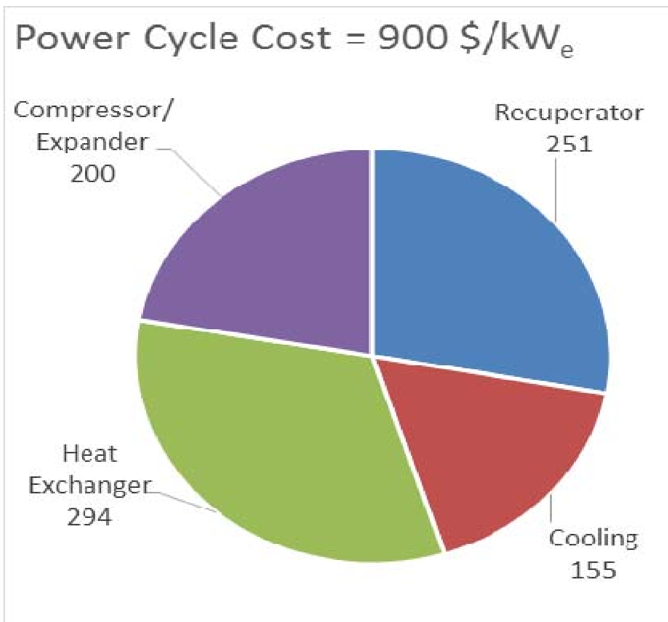
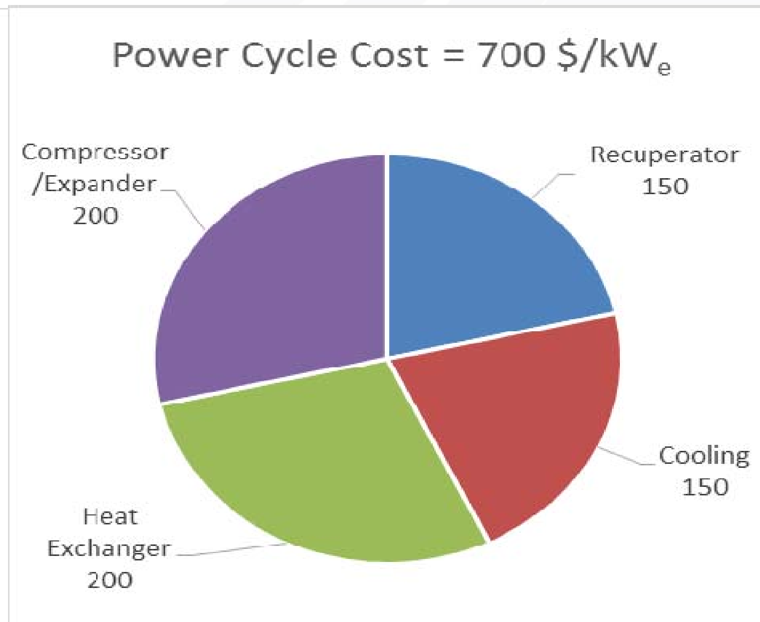
Power Block Cost Improvements: Background



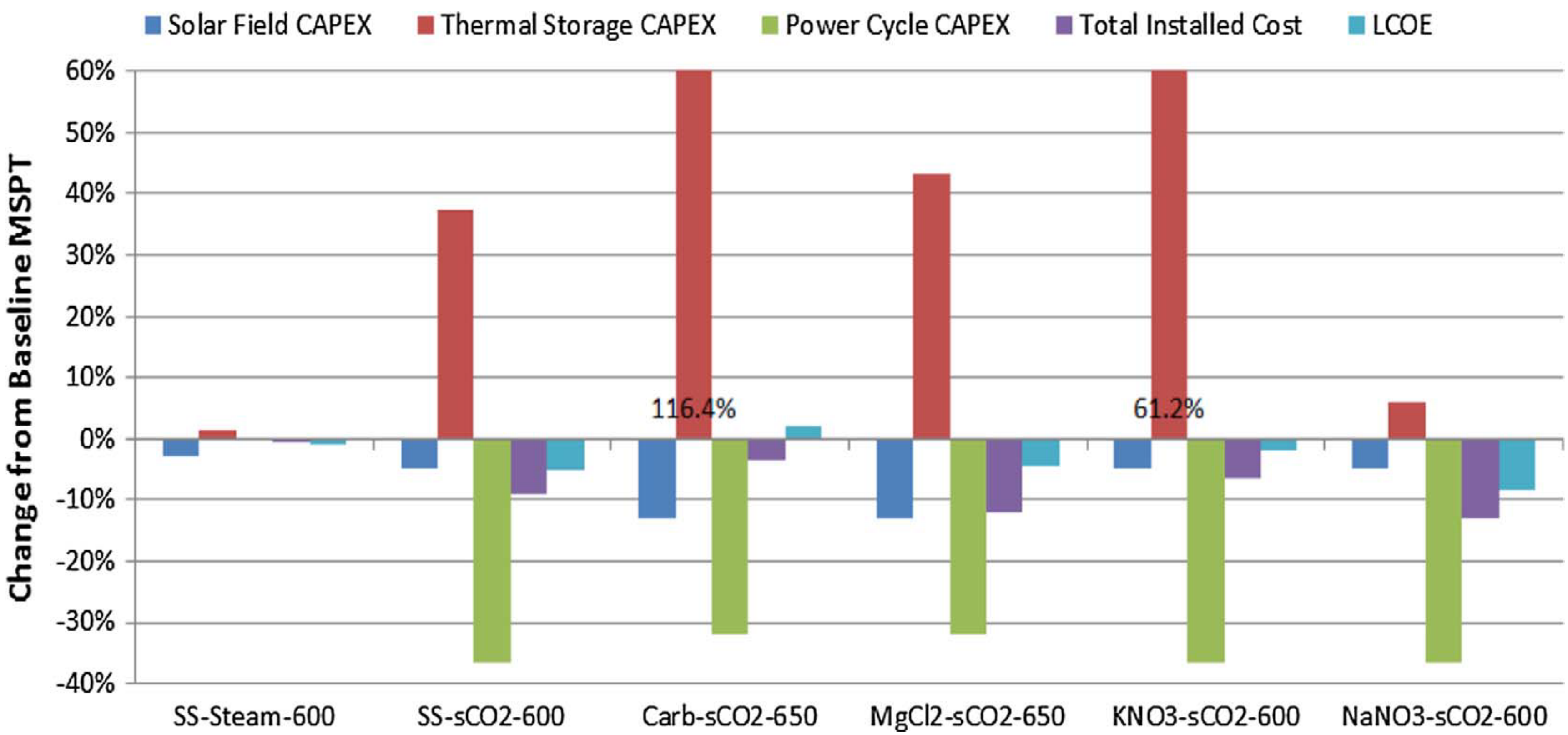


Primary heater ΔT

- Background
  - Thermal Energy System Integral to Molten Salt CSP Units
  - Large Diameter Tanks with Targeted and Actual cost of 15 $/kWth and 27 $/kWth
  - Tank Size and Cost Increases Due to a Combination of Lower ΔT and More Modest Properties, when Chlorides Substituted for Nitrates

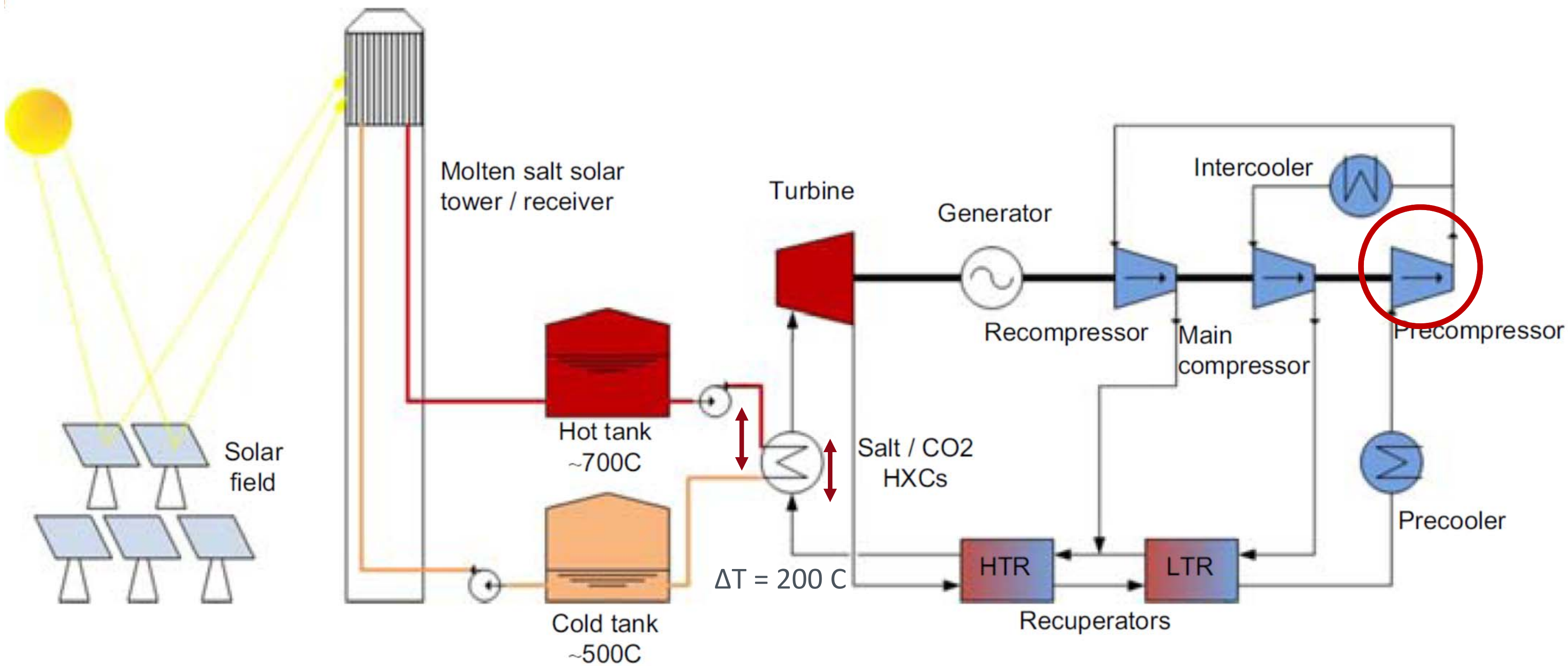
Salt	Average Density	Average specific Heat	Thermal Energy Storage	ΔT	Volume of TES	Volume of Tank	Height of Salt Tank	Diameter of Salt Tank
	kg/m³	kJ/kg.K	MWh	°C	m³	m³	m	m
Nitrate	1750	1.53	3,000	270	14,341	15,000	20	31
Ternary Chloride	1900	1.14	3,000	180	27,583	29,000	20	43

Cost and LCOE Changes Arising from Moving to High temperature Salt/sCO2 Cycle

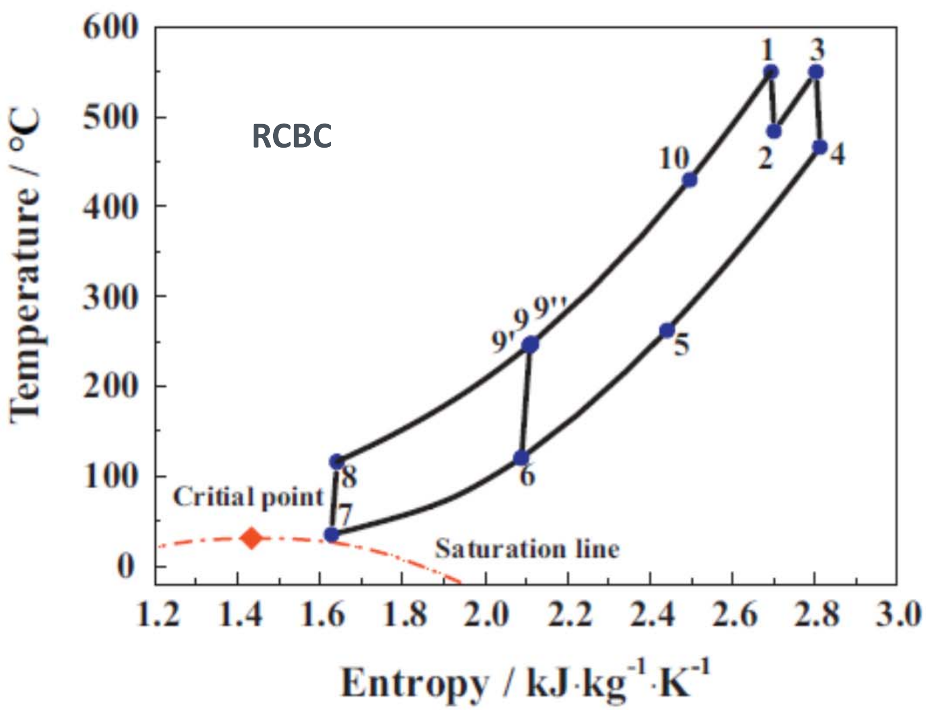


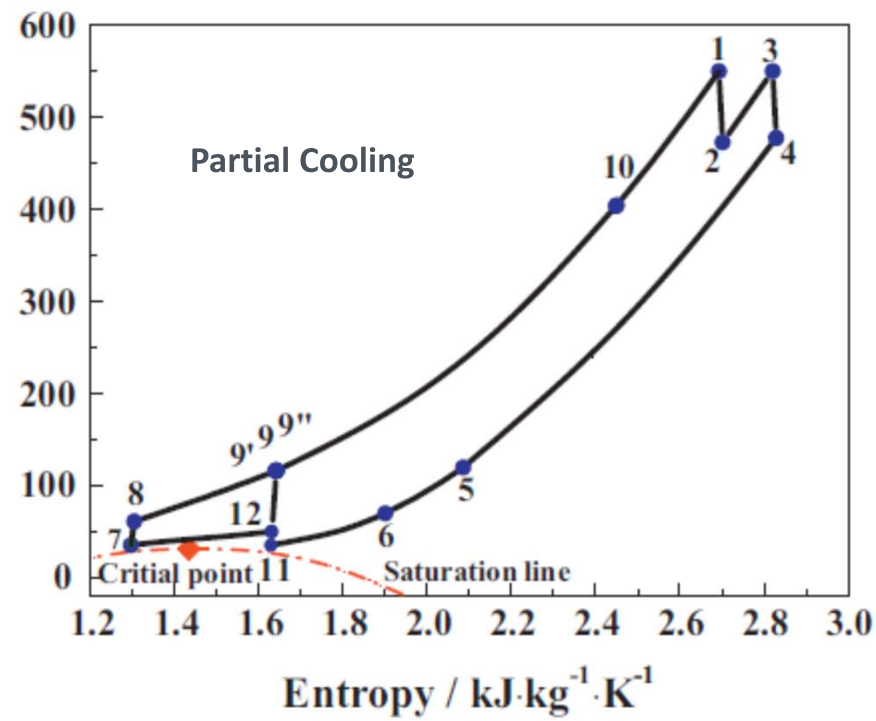
Molten salt power towers operating at 600–650 °C: Salt selection and cost Benefits Craig S. Turchi , Judith Vidal, Matthew Bauer. Solar Energy 164 (2018) 38–46

Power Cycle Modification for a Broader ΔT Across the Primary Heater



A Partial Cooling Cycle to Accommodate a Broader ΔT Across the TES





Near Term sCO_2 Power Cycle Needs for CSP

- Higher Heater ΔT at a given turbine inlet temperature for Partial Cooling Cycle compared with RCBC; ΔT ~270 C Matches with TES Requirements of CSP (Ref. Kulhanek)

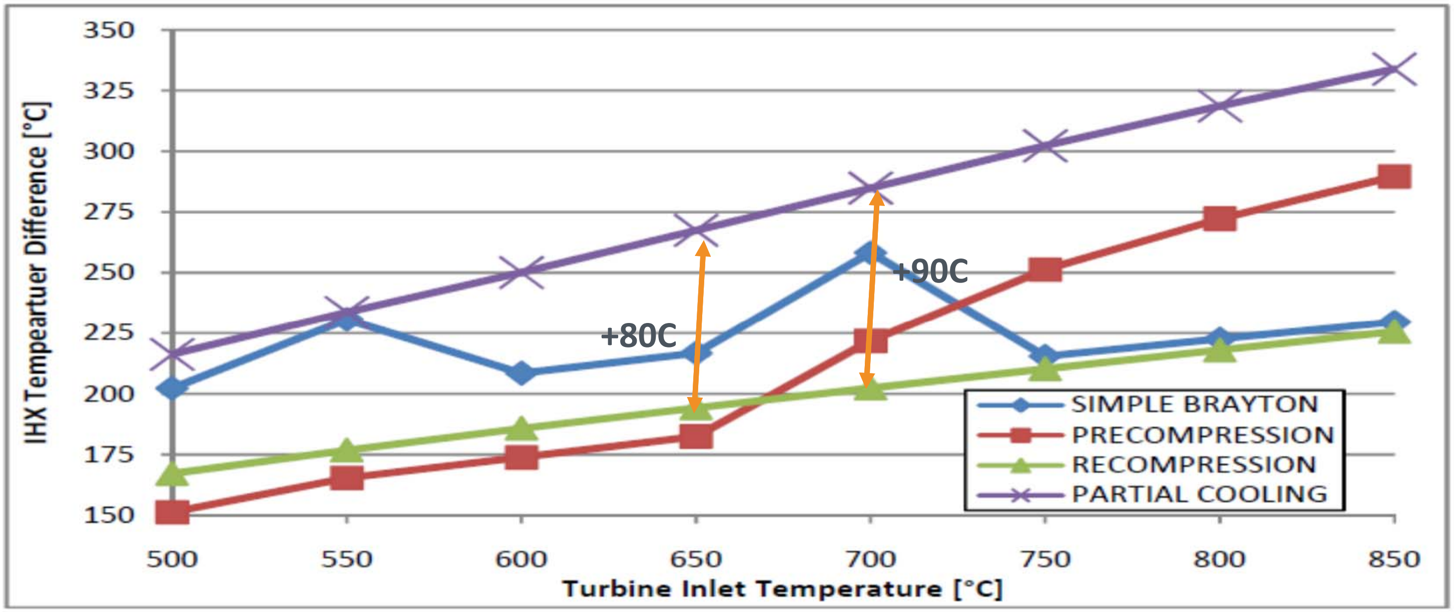


Figure 3 - Comparison of IHX Temperature Difference at Various Turbine Inlet Temperatures (25MPa)

HTF-to-sCO_2 Heat Exchanger

- SETO-Funded Research Focused on:
  - Molten Salt-sCO2 Heat Exchanger
    - Novel Cermet to withstand high temperature and corrosion from both, molten salt and sCO_2
    - Manufacture microchannel heat exchanger using cermet; has not been tested in flowing molten salt
  - Solid Particle-sCO2 Heat Exchanger
    - New parallel plate (embedded channels) moving bed heat exchanger
    - To be tested in falling particles/sCO_2
  - HTF-to-SCO2 heat exchanger is a Critical Component to Make the Transition to sCO_2 Cycle Work
  - Need Careful Consideration of System Design for cold startup, hot startup and shutdown

PreCooler Needs for CSP: Air Cooled Heat Exchangers

- Dry Cooling for Precoolers
  - Seinecki Group at ANL Investigated Large Air Cooled Cross Flow Finned Tube heat Exchangers
  - Cost Estimate Below 150 $/kWth; airside ΔP of 0.2 kPa; 5 MW Air Cooler Power for Removing 132 MWth
  - PCHE cost was found to be Excessive
  - Sandia/VPE design of Parallel Plate Embedded Channel Air cooled Heat Exchanger in Progress
- Use of Waste Heat from sCO_2 Cycle
  - Waste Heat from 100-32 °C Available, and More than 50% of the Input Heat
  - Innovations Such as Using the Waste Heat for Compressor Inlet Chilling Using Heat Pumps Possible, Particularly when Air Temperature is Low
  - Availability of Waste Heat at such a Broad Range Unique to SCO2 and awaits the Use of Novel Cycles for Recovery

Operations and Maintenance Innovations Needed

- CSP Plant Operators in Remote, Desert Locations; do not have Personnel to Operate both, a CSP Unit and a Novel Power Cycle
- A Forgiving Power Cycle Required
- Autonomous Operation and Minimum Operator Action Required to Support a Plant O&M Cost Goals (Fixed $10/kW-year and Variable $1/MWh)

Summary and Conclusions

- CSP-Specific Needs for the sCO_2 Cycle were Identified
- Six Specific Areas of Action and Improvement were Identified
- High Turbine Inlet Temperature for 50% sCO2 Cycle Efficiency Leads to High Heat Transfer Fluid Outlet Temperatures and Translates to High TES Storage Cost and High Costs for Piping
- Not Readily Clear that LCOE Goals can Coexist with 700 C Turbine Inlet Temperature Goals
- Might be More Prudent to seek Efficiency Improvements and Cost Improvements at Even Lower Turbine Inlet Temperatures
- Seek to Re-Align Power Cycle cost and efficiency Goals with new SETO LCOE Cost Targets