Application of an Integrally Geared Compander to an sCO_2 Recompression Brayton Cycle

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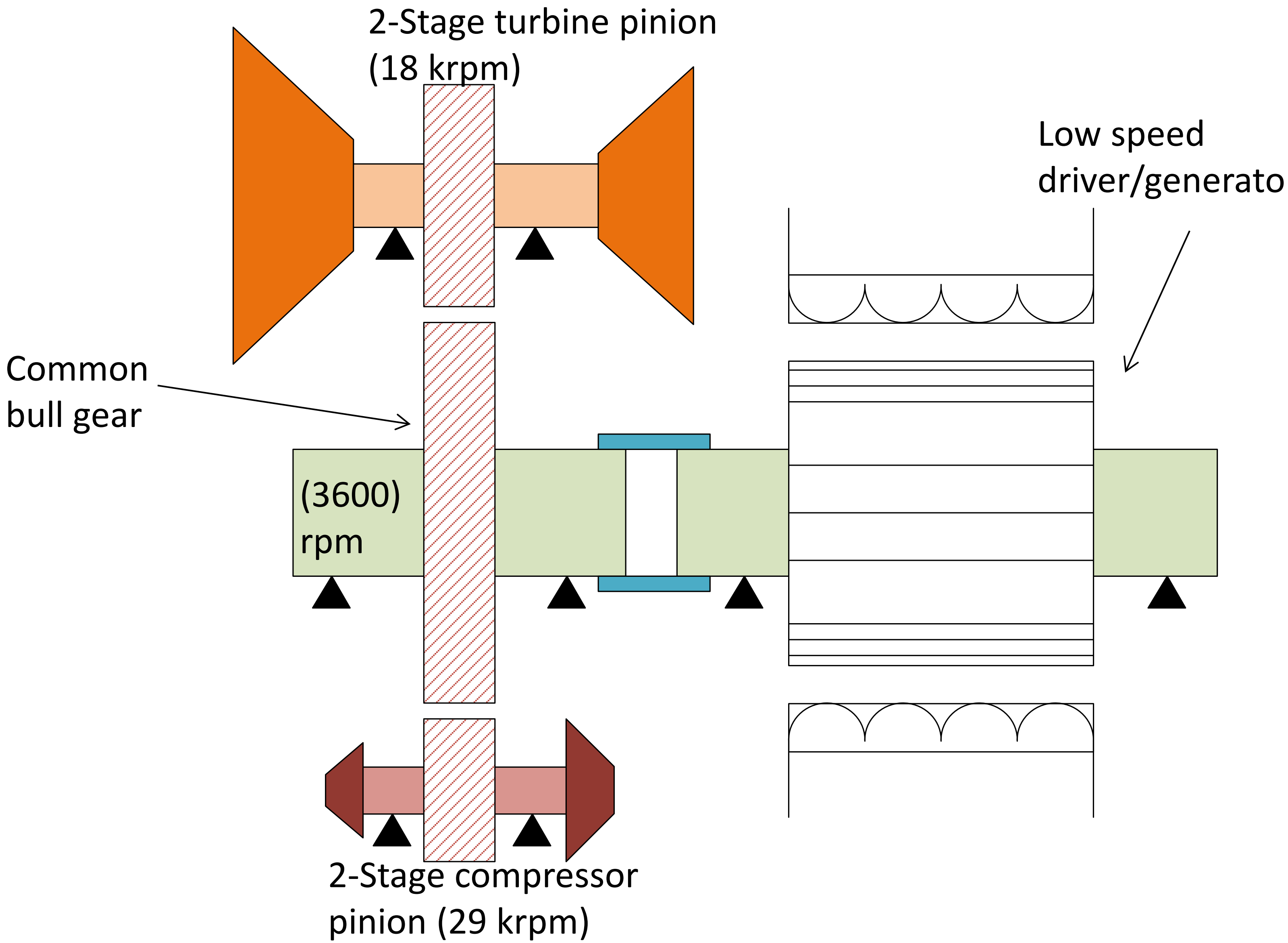
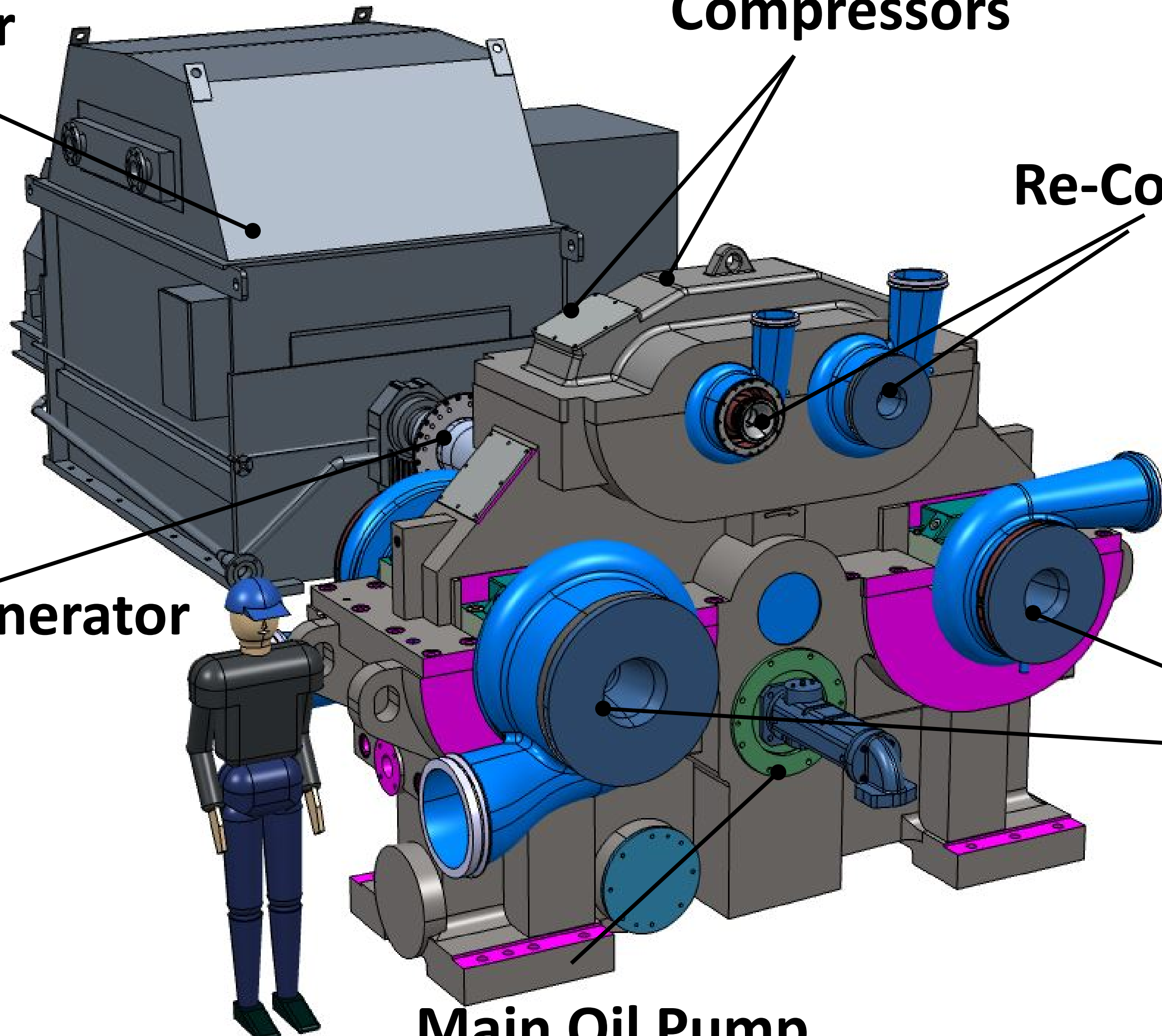
sCO_2
Supercritical CO_2 Power Cycles Symposium

An integrally geared compander is composed of pinions having compressors and turbines geared to a common shaft



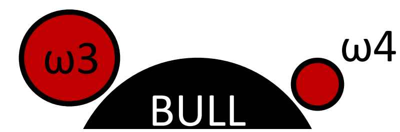
An IGC allows for an interesting power block concept for S-CO2 Brayton cycles and alternative cycles

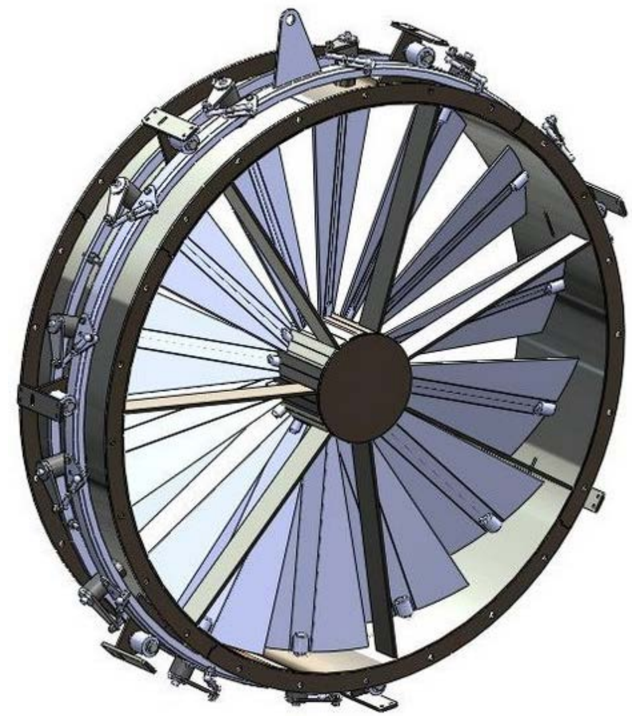


IGCs naturally allow for features that need to be explored to optimize cycle efficiency and reduce LCOE

- Pinions may rotate at different speed to allow for improved stage efficiencies
- IGC commonly employ flow control features
  - Inlet guide vanes
  - Variable diffuser vanes
  - Variable nozzles
- Intercooling and reheating are easily implemented

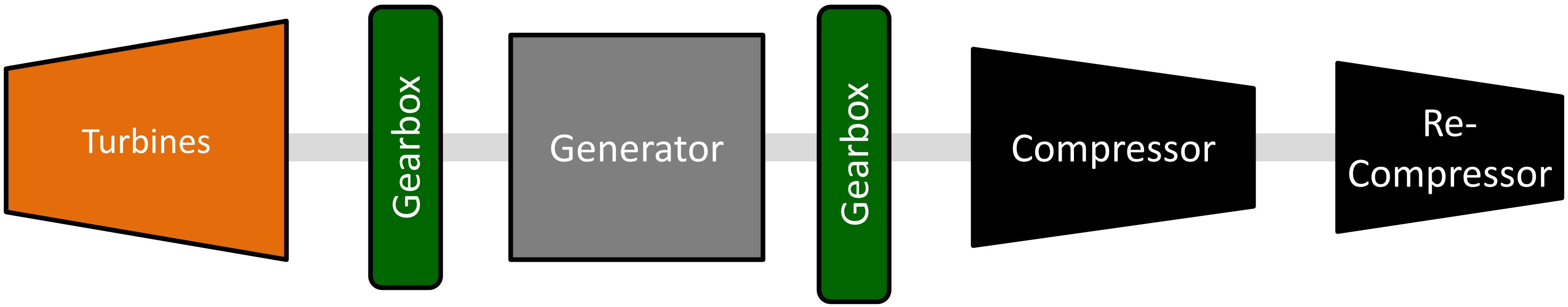
$\omega1<\omega2<\omega3<\omega4$



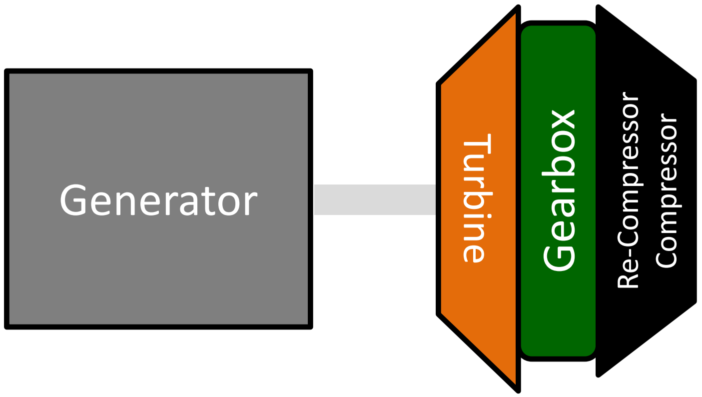


An IGC package incorporates all the key elements of a conventional train in a compact modular package

Conventional Turbomachinery Train



Typical IGC Package

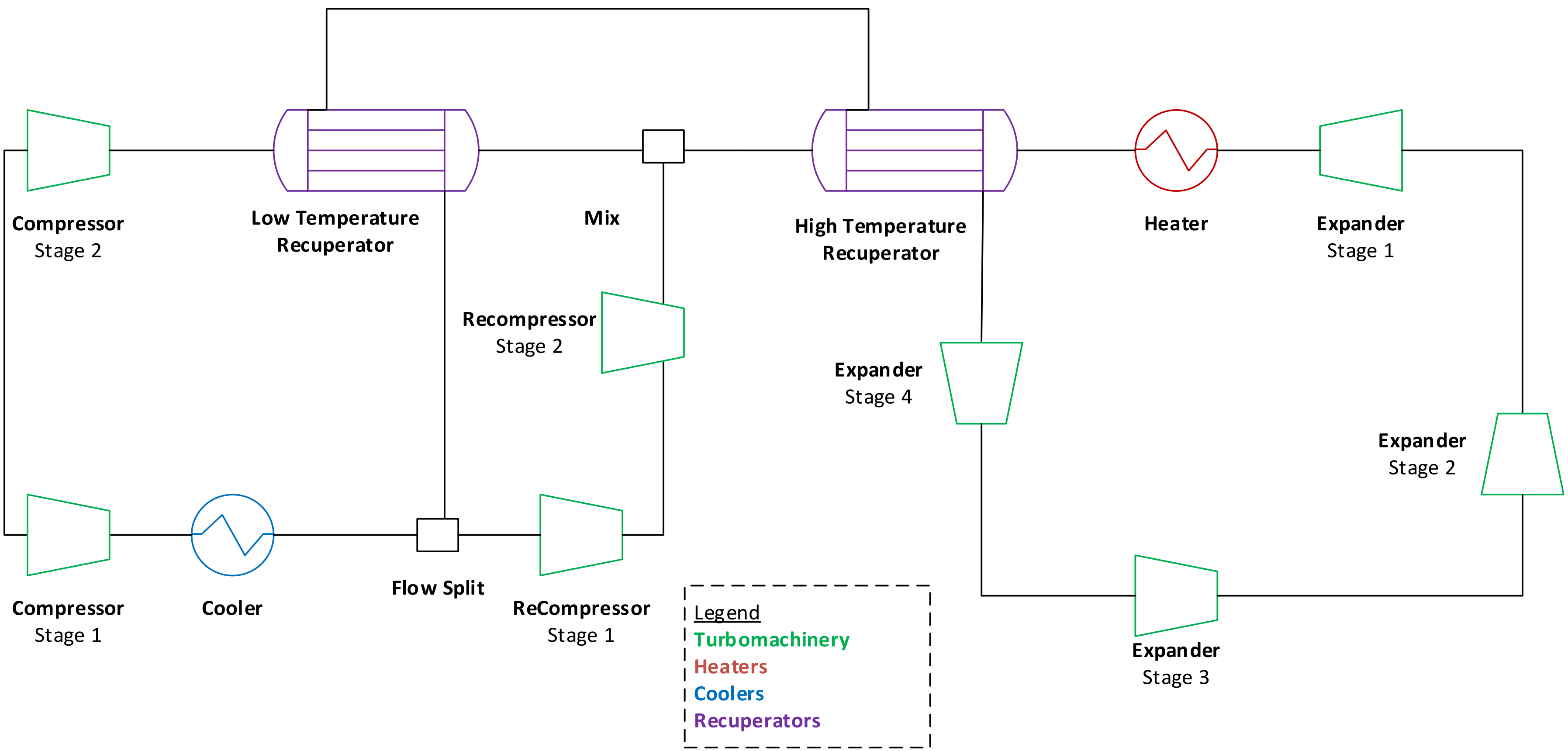


- Compressor, re-compressor, turbine and gearbox are assembled in a single compact core.
- The second gearbox, additional couplings and housings in the conventional train can be eliminated
- Simple IGC package can potentially reduce costs by up to 35% (Based on very little concrete data)

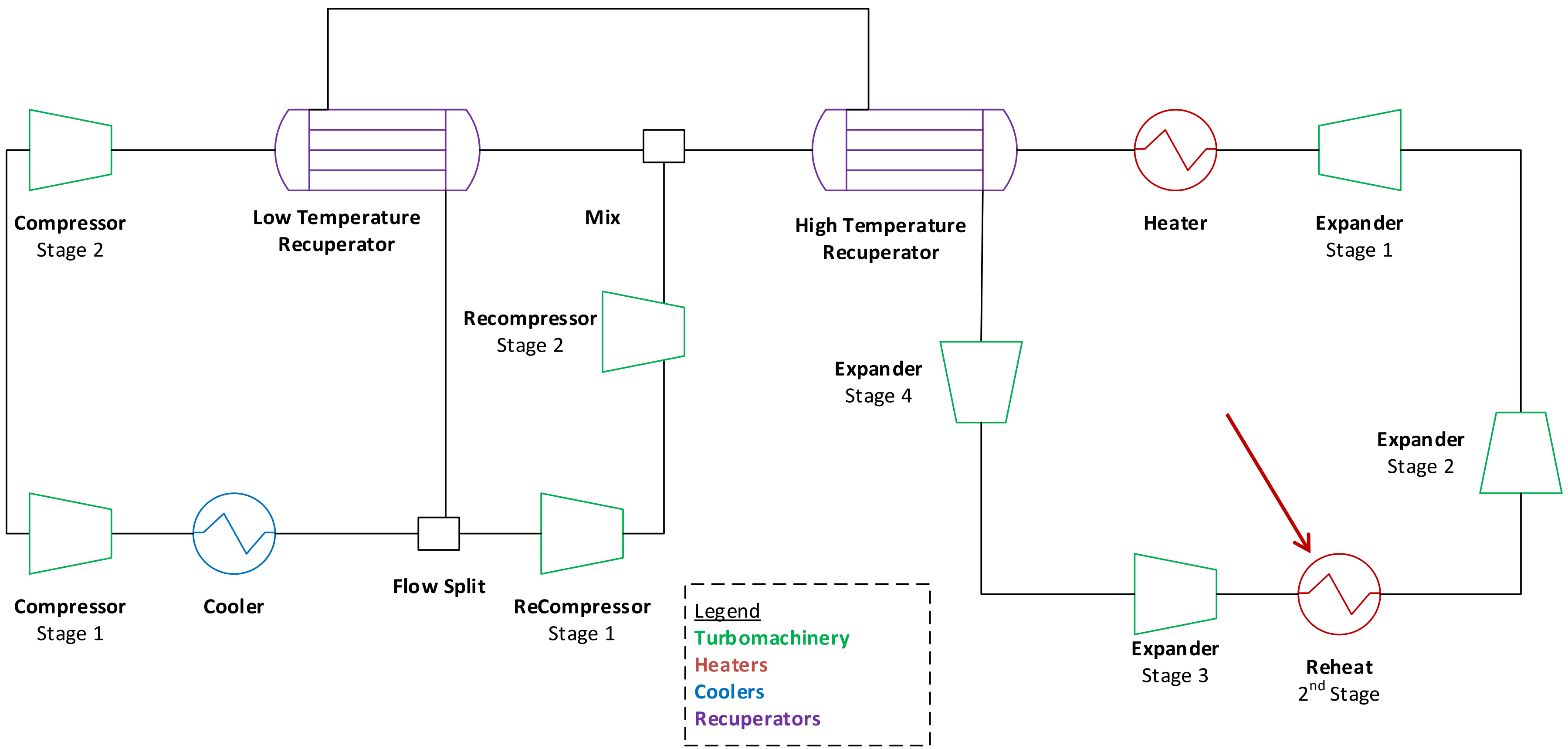
The 10 MWe Scale IGC cycle was optimized under the constraints of the APOLLO FOA

Group	Property	Value
Heat Exchanger	Pressure Drop (each Heat Exchanger)	1 %
	High Temp Recuperator Effectiveness	97 %
	Minimum Pinch Temperature	5 °C
	Heater Outlet Temperature	705 °C
	Cooler Outlet Temperature Range	35-55°C
Generator and Mechanical Efficiencies	Generator Efficiency	98.7%
	Compressor Mechanical/Pinion Losses	4%
	Turbine Mechanical/Pinion Losses	2%
Pressure Limits	System Min Pressure	1,070 psia
	System Max Pressure	3,953 psia
Turbomachinery	Compressor Isentropic Efficiency	83.5%
	Re-Compressor Isentropic Efficiency	84%
	Turbine Isentropic Efficiency	92%

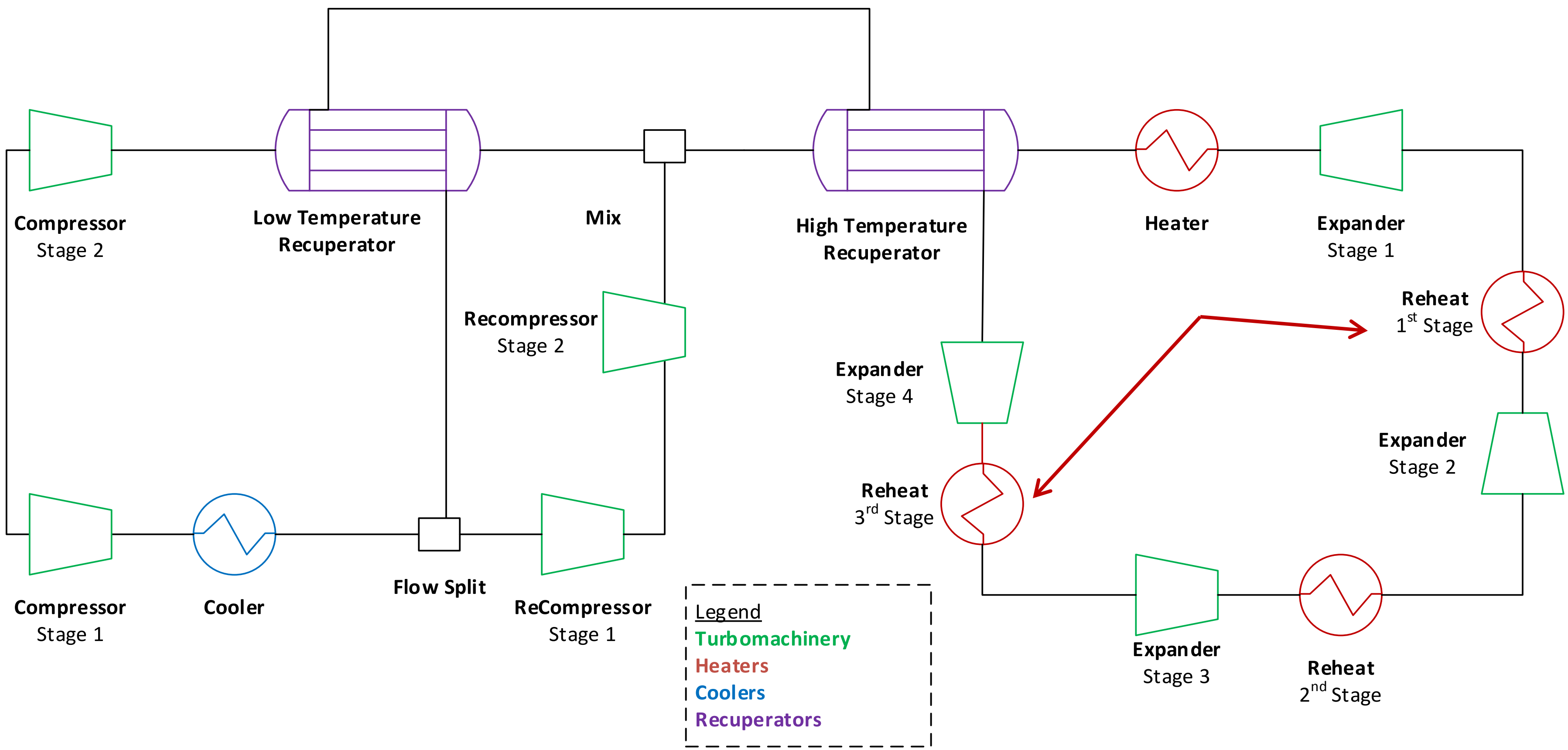
A simple recompression cycle at 55° was chosen as a "representative baseline" for proposed CSP SCO2 cycles



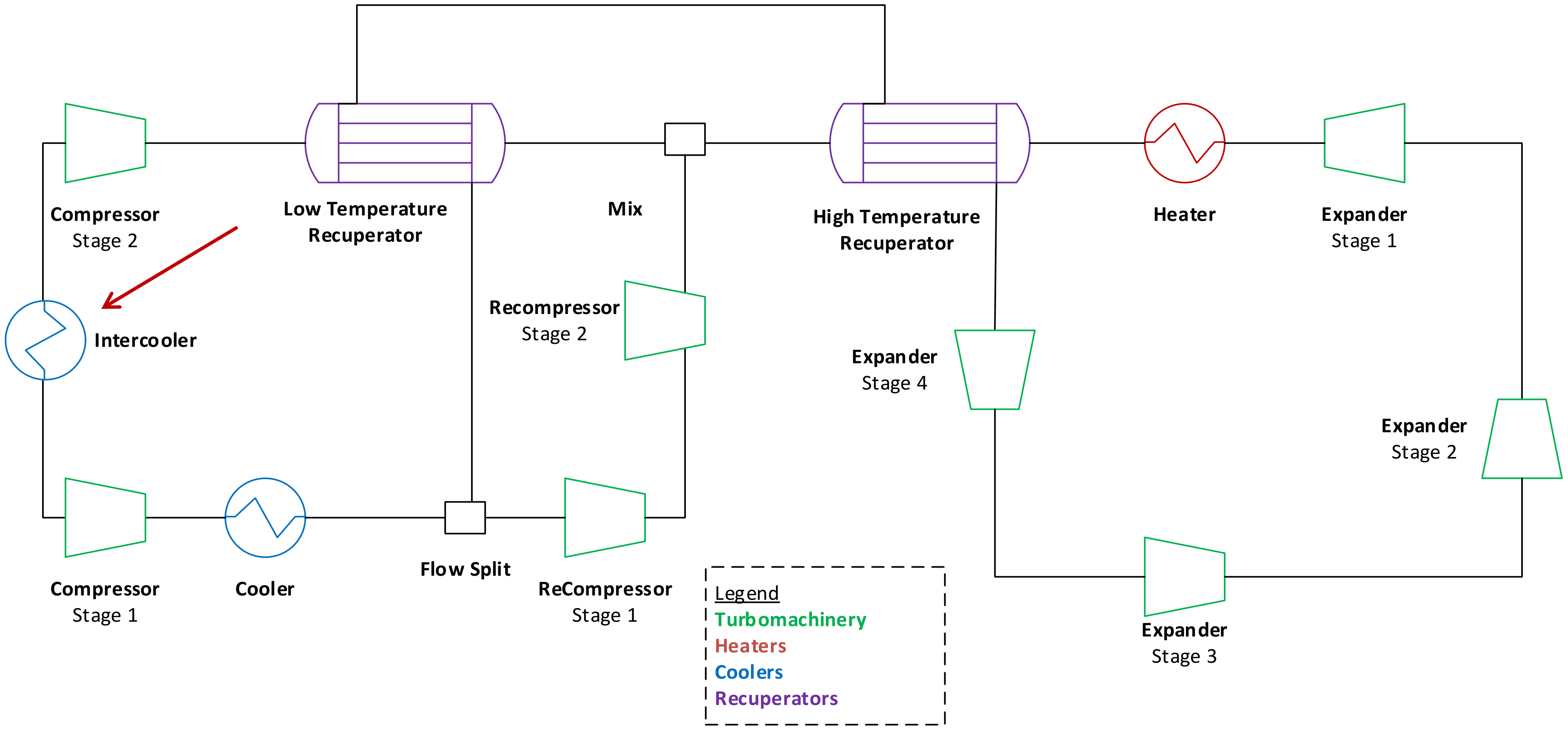
Single stage turbine reheating (after S2) was added and an efficiency gain of 0.5-1% was noted



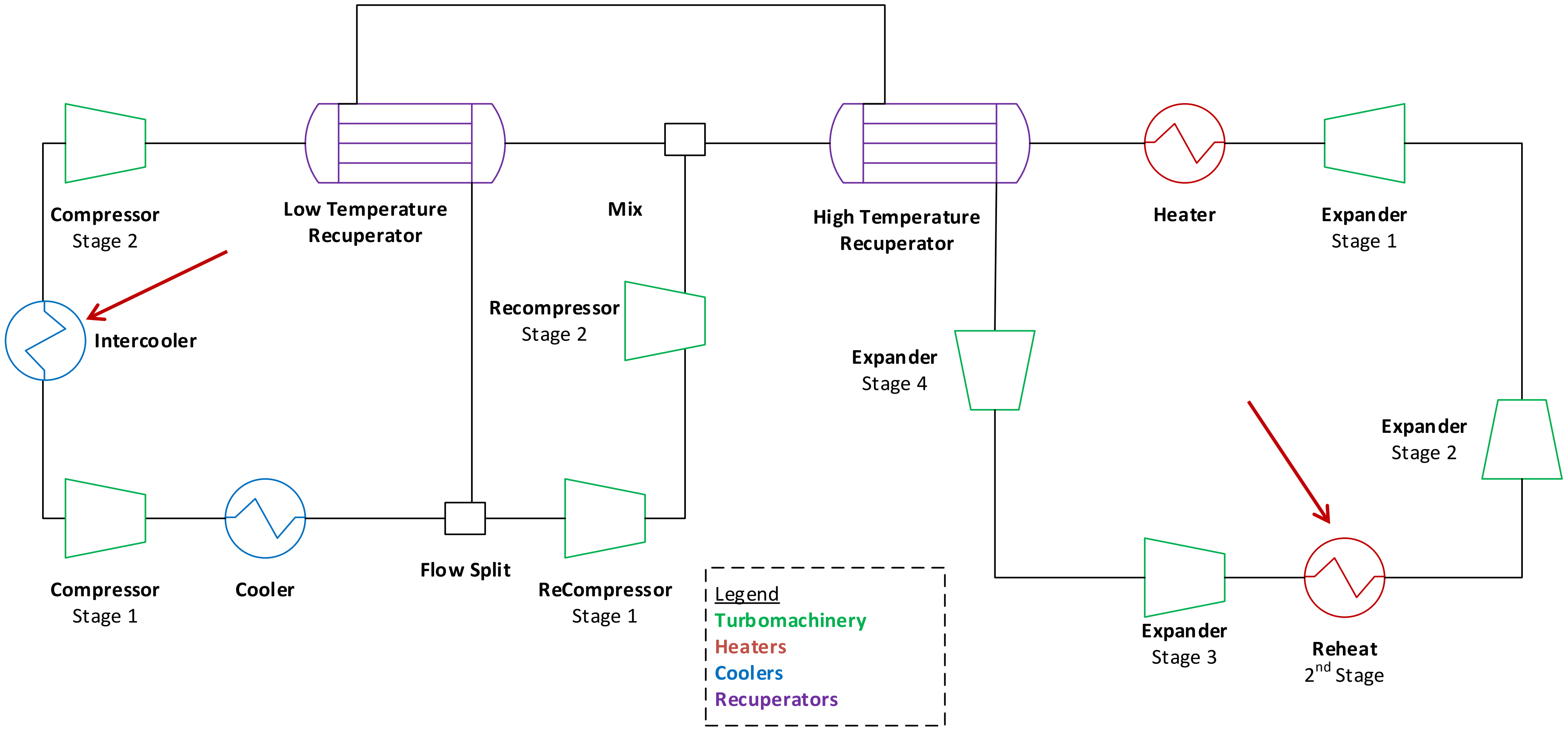
Additional reheat stages decreased efficiency due to pressure losses in the heat exchangers



Intercooling was added and showed improved efficiency for higher pressure ratio cycles

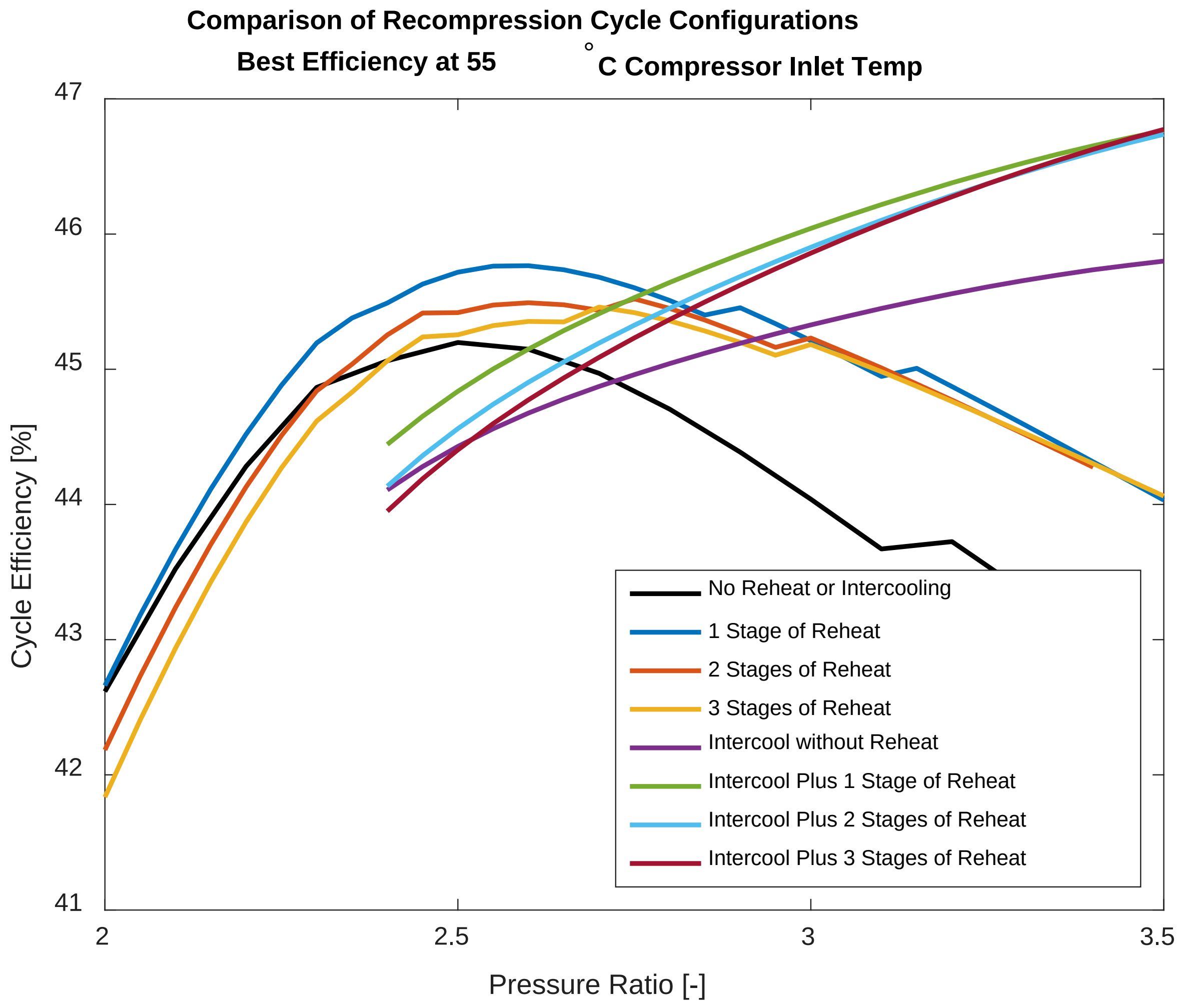


Intercooling plus reheating showed similar trends with further improved efficiencies for higher pressure ratio cycles

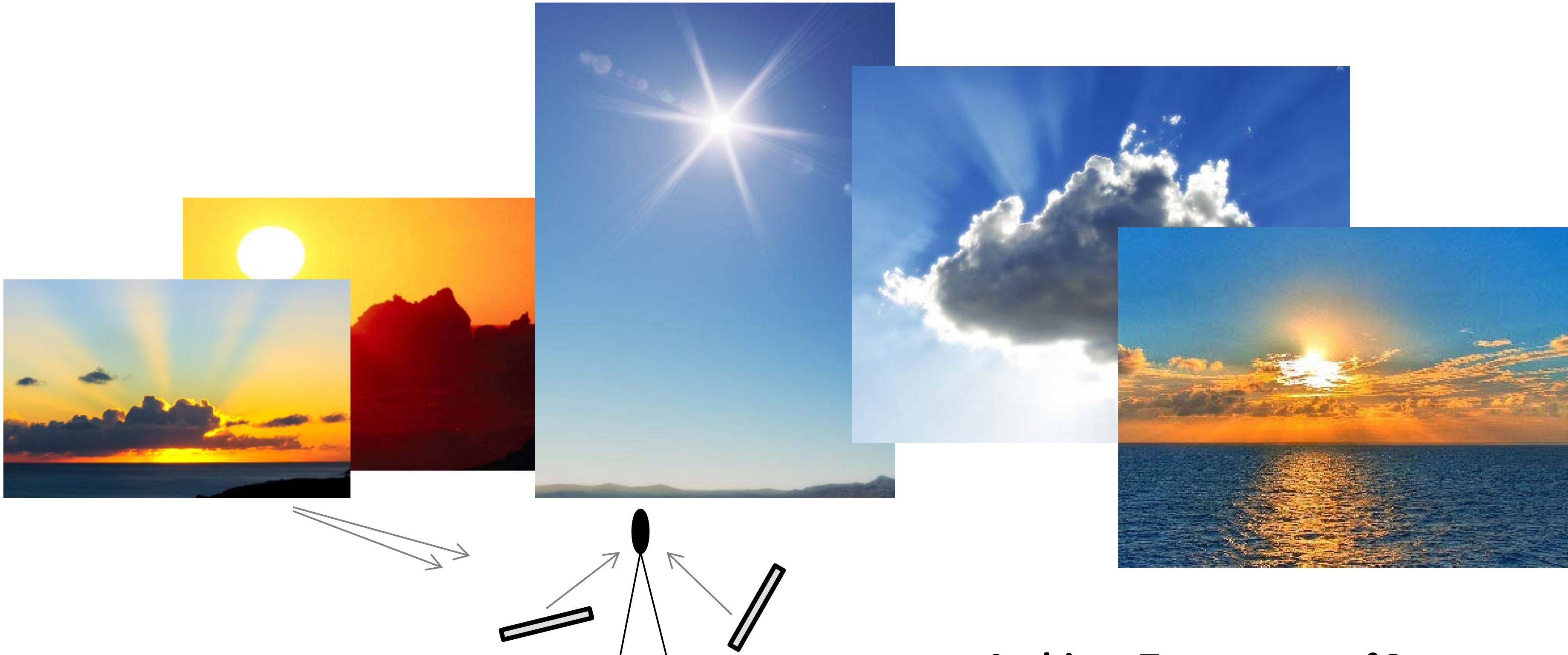


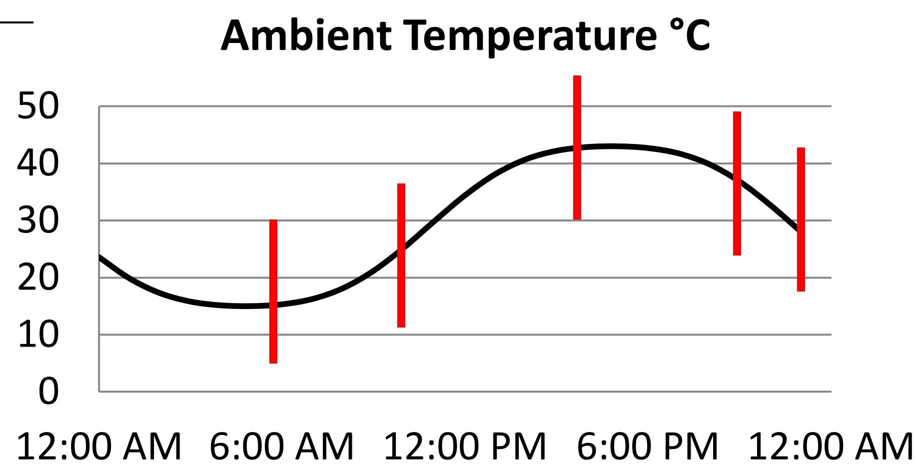
Optimal efficiency and cycle configuration is dependent on a number of variables

- Pressure Ratio (PR)
  - Optimal PR varies with cycle configuration
  - Intercooling favors higher PR
- Turbine Reheat
  - Single stage improves efficiency 0.5-1%
  - Pressure drops in reheater reduce cycle efficiency for multiple stages of reheat



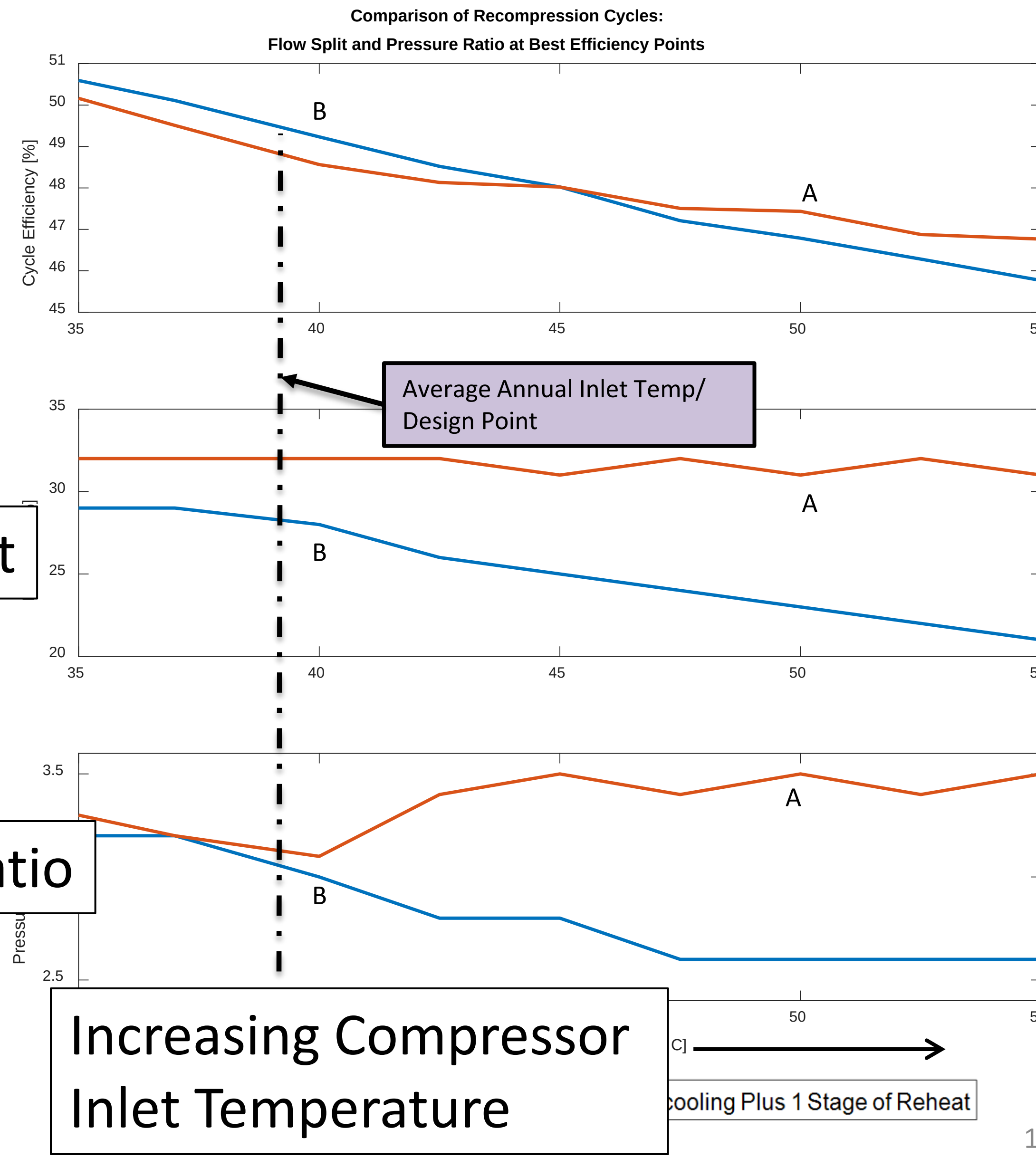
The transient challenges of a concentrated solar power plant are significant





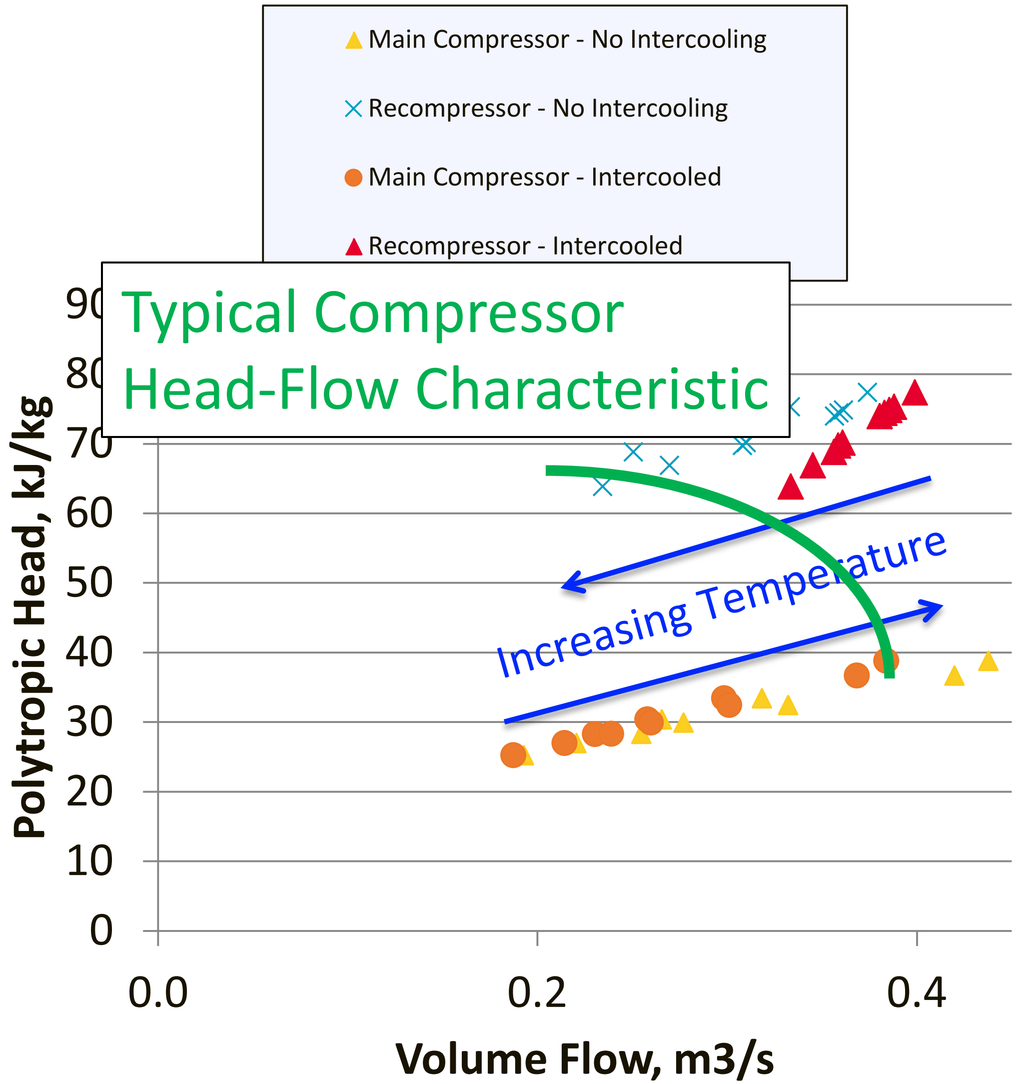
Is high peak cycle efficiency really the target?

- SAM modeling of typical s… s shows an annual average compressor inlet temperature to be 37-38ºC assuming 15ºC approach temperature in the cooler
- Cycle Modeling
  - Optimal flow split
    - 22-33%
    - Heavily dependent on CIT
  - Optimal PR
    - Varies with us
  - Intercooled cy… more efficient on hot days, and less efficient on cool days

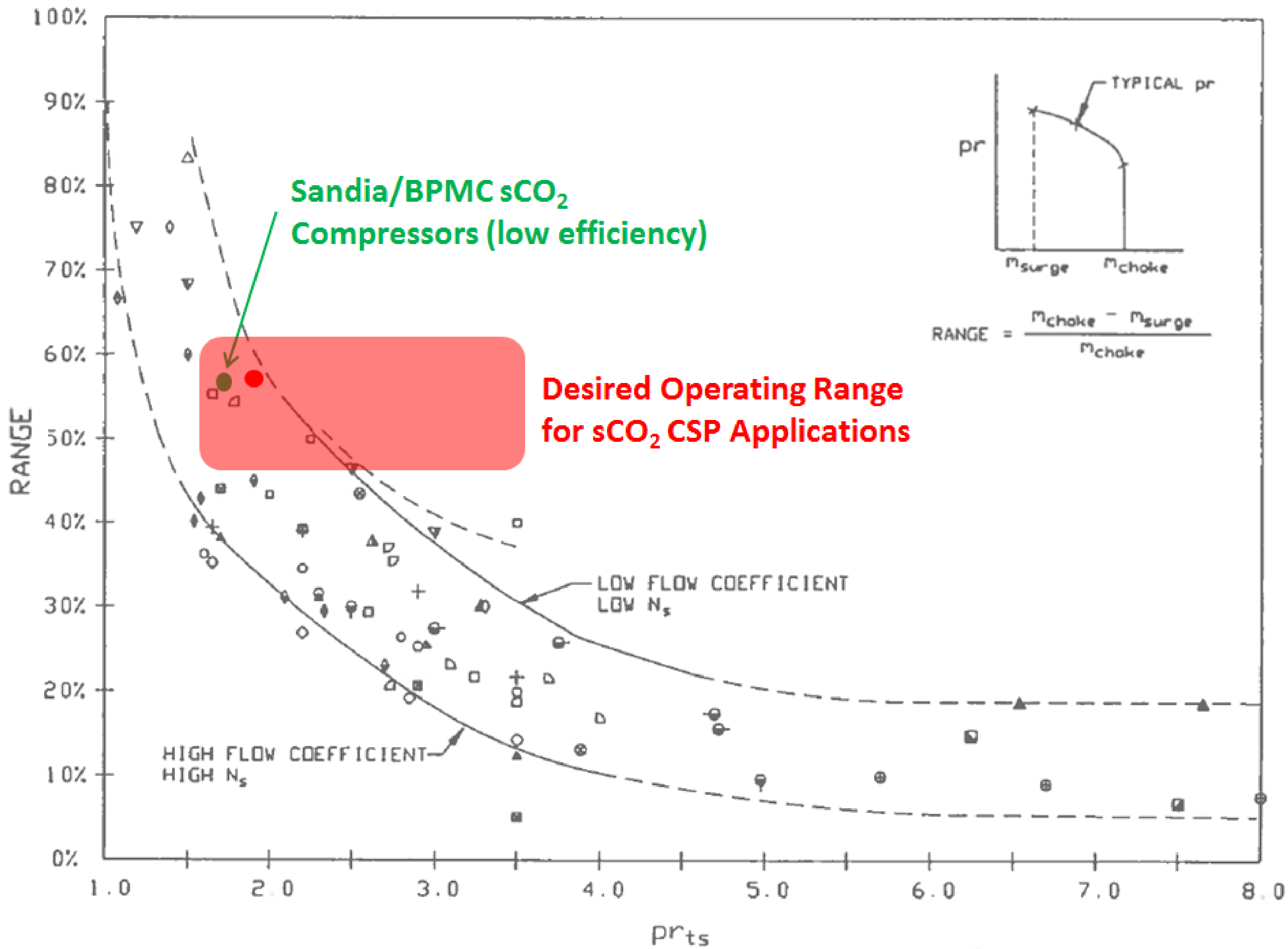


Wide-Range impeller operation is essential to optimizing cycle efficiency

- Range Requirements at Optimal Efficiency Condition (without using range reduction techniques)
  - Compressor > 55%
  - Recompressor > 37%
- Control Strategies
  - Alter flow split and pressure ratio to reduce compressor requirements
  - Control compressor inlet temperature
  - Employ inlet guide vanes

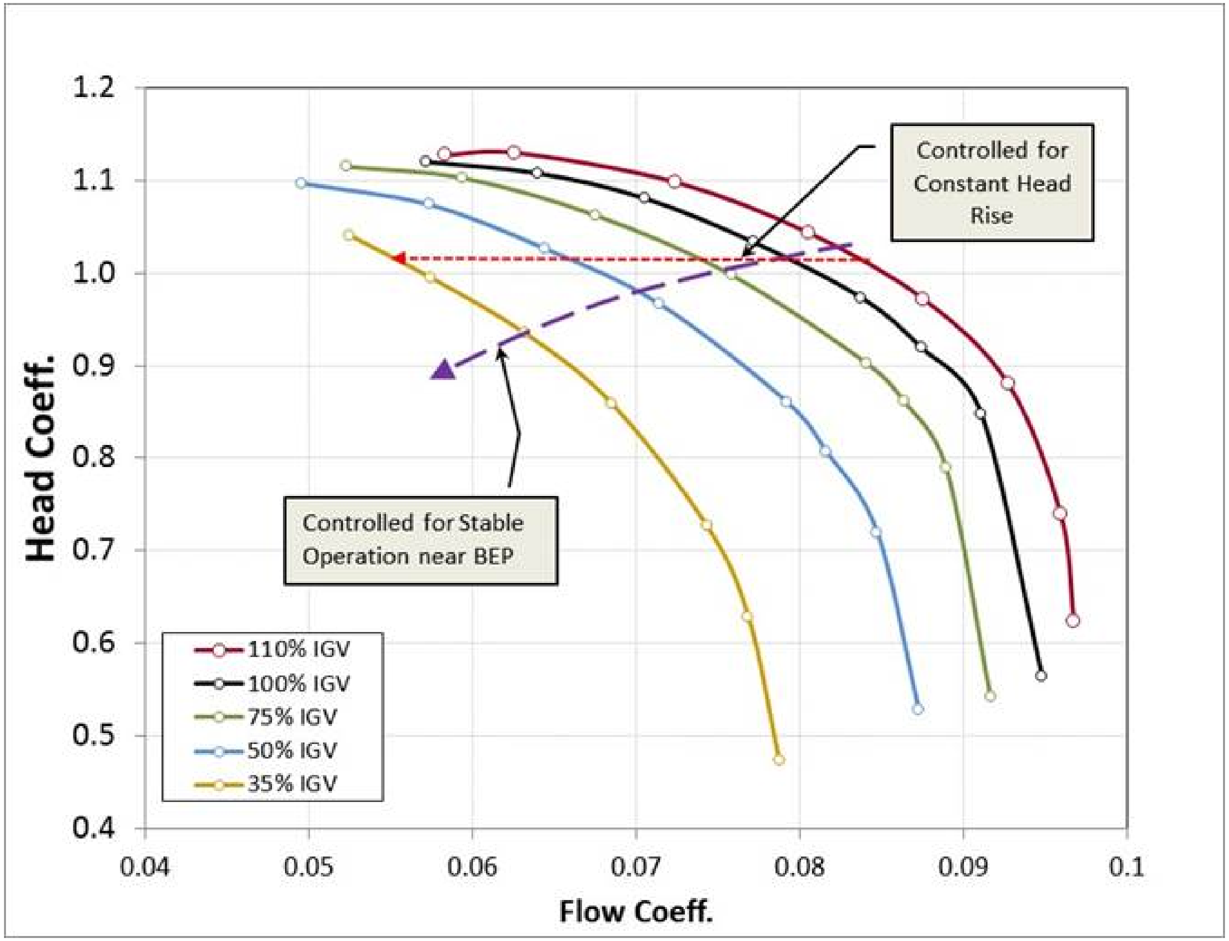


Range requirements for the compressor exceed current technology capabilities



IGVs may be an essential feature in adapting to varying compressor inlet temperatures

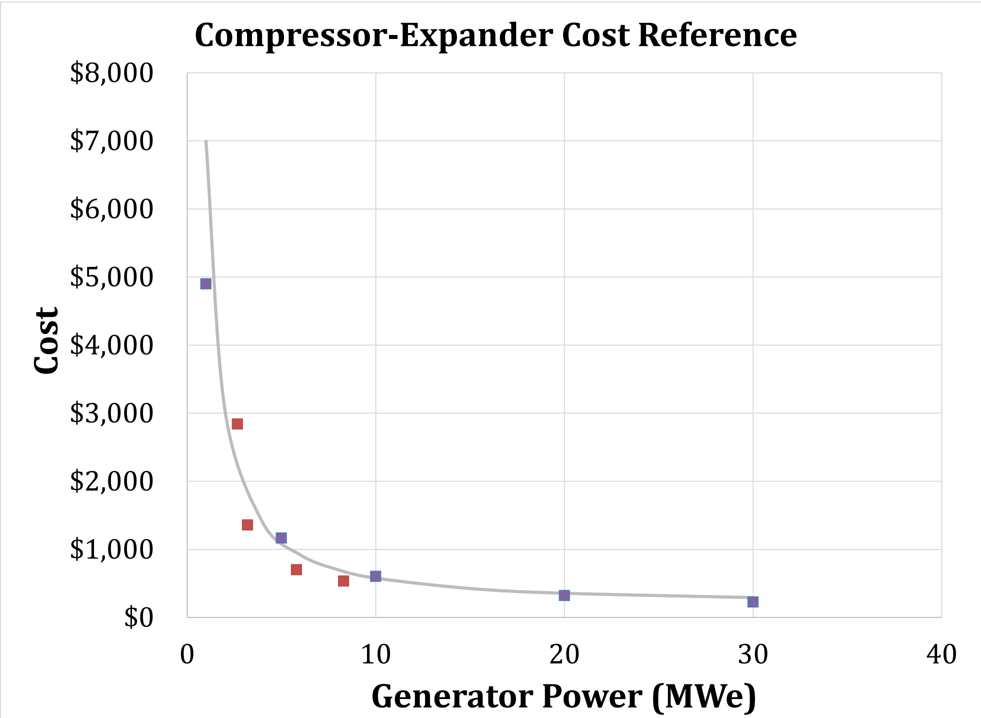
- Inlet Guide Vanes
  - Can be actuated to produce similar head flow characteristics as required to obtain an optimal solution
- Alternate strategies also exist

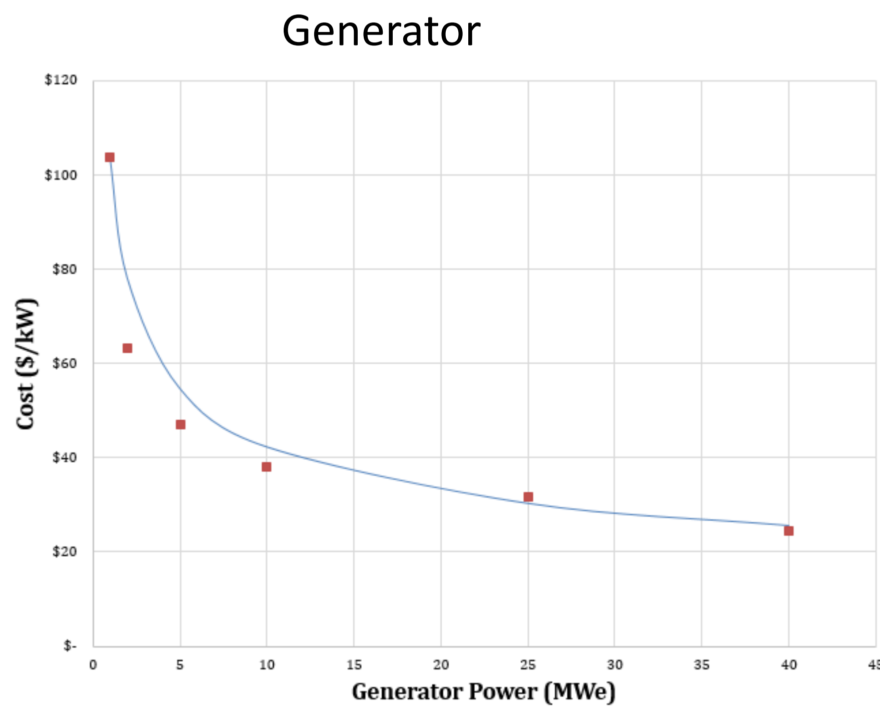


Who really cares about efficiency?

Really, it is money that is important

Cost estimation of turbomachinery is promising





- Compander
  - 400-600 $/kWe depending on compander size
  - Highest cost component on the train
- Generator
  - Readily available
  - Relatively small portion of total $/kWe

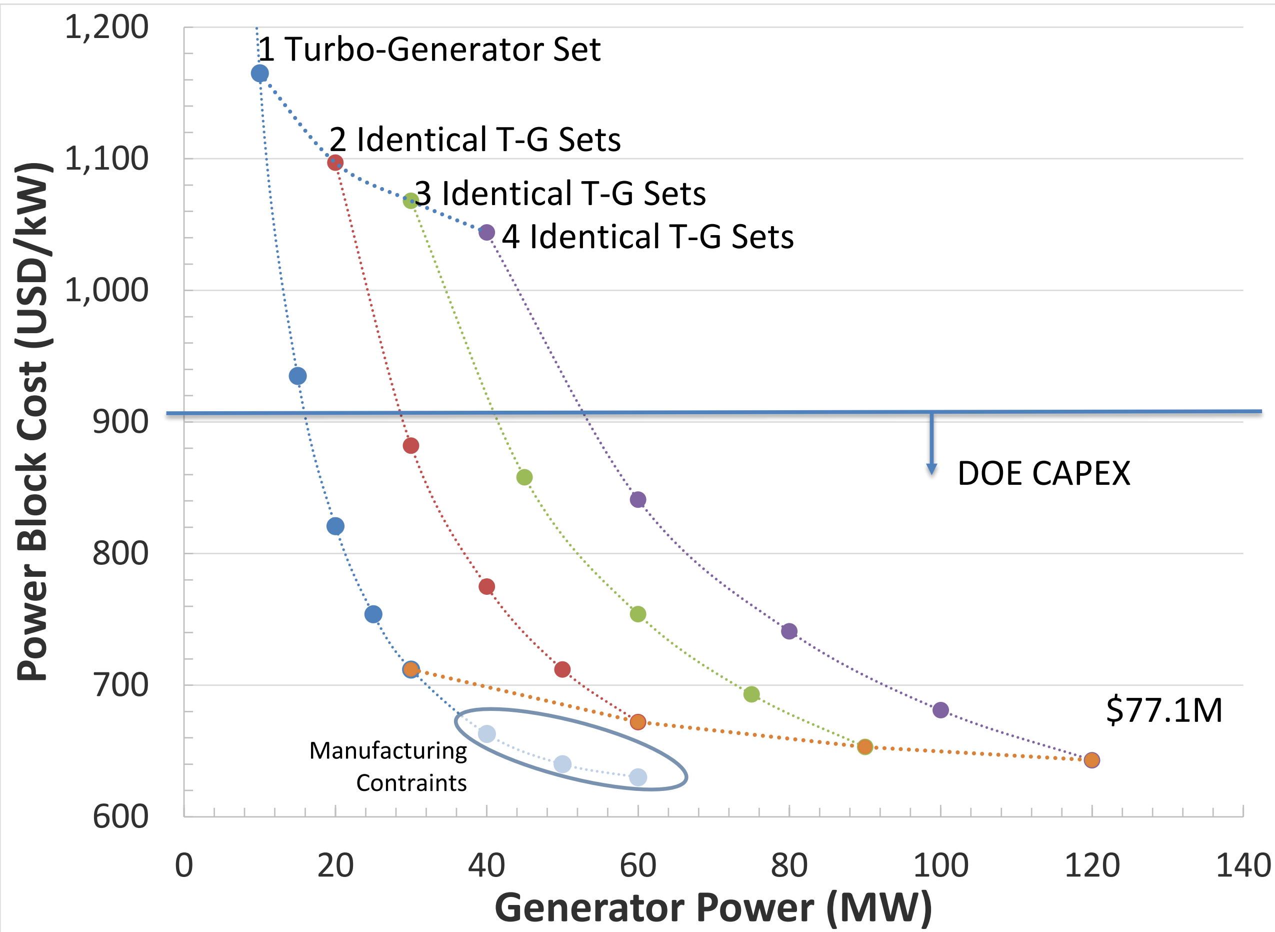
Very little published data exists on rules of thumb for calculating HE costs

- Heat Transfer
  - Total Cost = 301.46 $\$/kW_{Gen}$
- Recuperator
  - Highest cost/kW transferred
  - Highest power transferred

Component	Duty Estimation ($kW_{Thermal}/kW_{Generator}$)	Cost Estimation ($\$/kW_{Thermal}$)	Cost Estimation ($\$/kW_{Generator}$)
High-Temperature Recuperator	3.990	50	199.5
Low-Temperature Recuperator	1.269	30	38.07
Primary Heater & Re-Heater	0.983	40	39.32
Cooler	0.983	25	24.575

Power block costs are expected to be meet the DOE APOLLO FOA targets

- Cost reduction achieved as the size is increased until the manufacturing limit is reached.
- Cost is reduced as multiple units are produced.

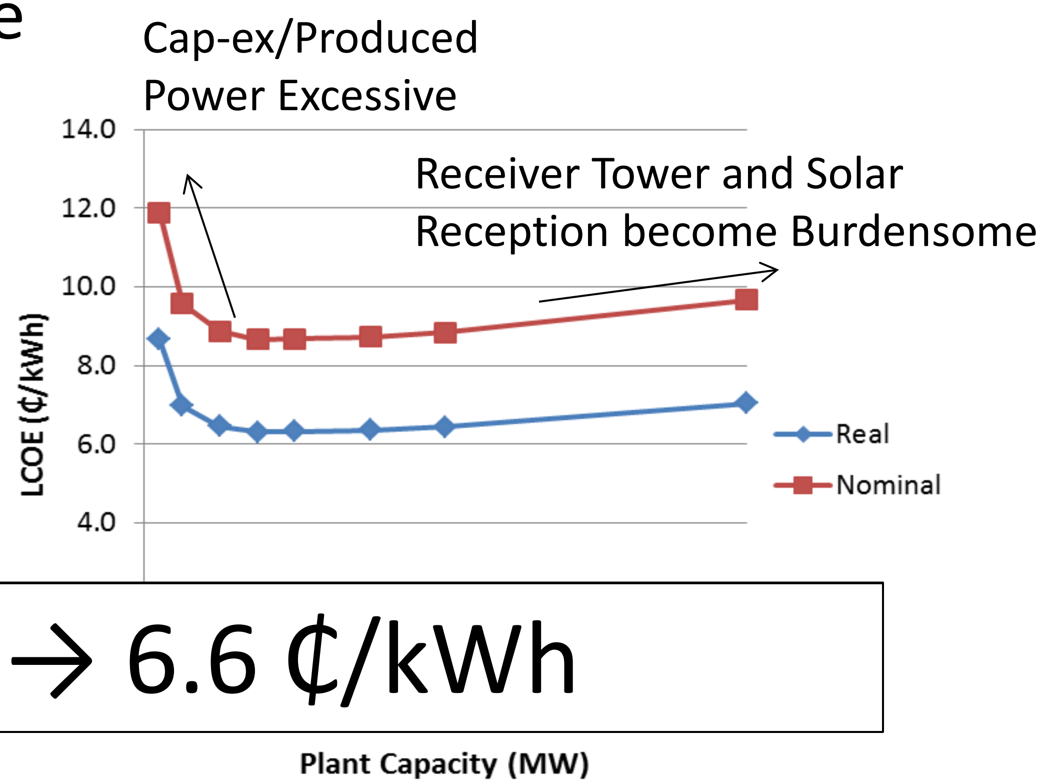


Deployment Strategy

- Initial 10MWe Nominal Design
- Scale to 20-25MWe in the same gearbox
- Produce at least 2 copies of the package to increase reliability
- Cost are expected to be below CAPX targets

Impact of LCOE vs. Scale shows a sweet spot for CSP in the 50-200 MW plant size

- SAM Model
  - Started with FOA requirements
  - Input target comp. efficiencies



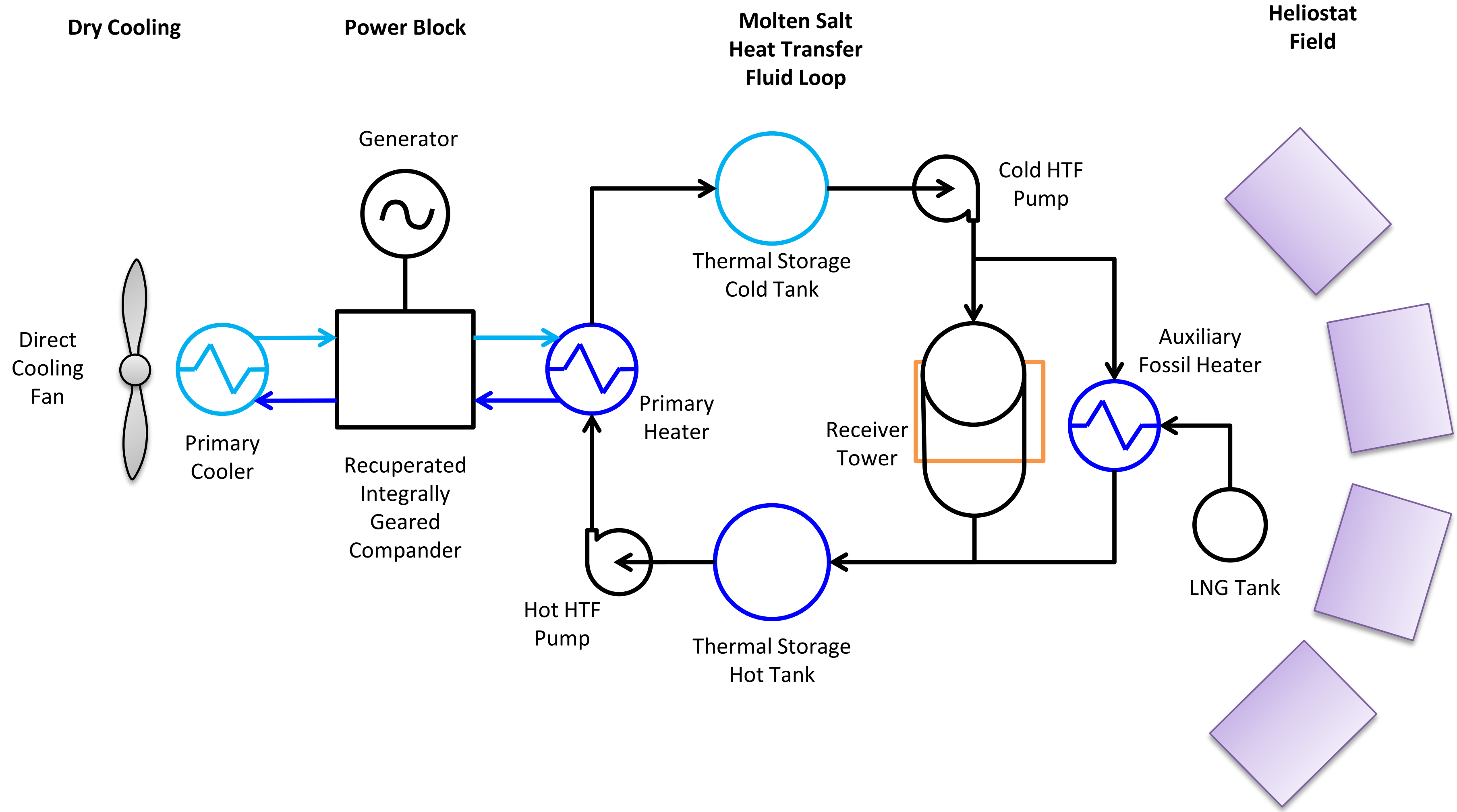
LCOE → 6.6 ¢/kWh

Key Parameters Targeted by FOA		Key Financial Parameters from SunShot	
Design HTF inlet temperature (°C)	720	Inflation rate (%/year)	3
PHX temperature difference (°C)	15	Real discount rate (%/year)	5.5
ITD at design point (°C)	15	Internal rate of return target	15%
Rated cycle conversion efficiency	50%	IRR maturation (years)	30
Power block cost ($/kW)	900	Loan duration (years)	15
Heliostat field cost ($/m^2)	75	Loan percent of total capital cost	60%
Thermal storage cost ($/kWh$_{th}$)	15	Loan annual all-in interest rate	7.1%

LCOE Optimization shows that the most likely path for CSP commercialization is to incorporate fossil assist

- CSP Optimization Study - Variables
  - Fossil assist: Utilize fossil heat when solar power is not available
    - Reduces LCOE because equipment is producing substantially more energy in the 30 year plant life
    - Reduces thermal stresses due to transient startup cycles
    - Various implementations exist depending on the thermal energy storage solution
  - Thermal storage options
    - Varied thermal storage from 0h, 12h, & 14h

Fossil Assist

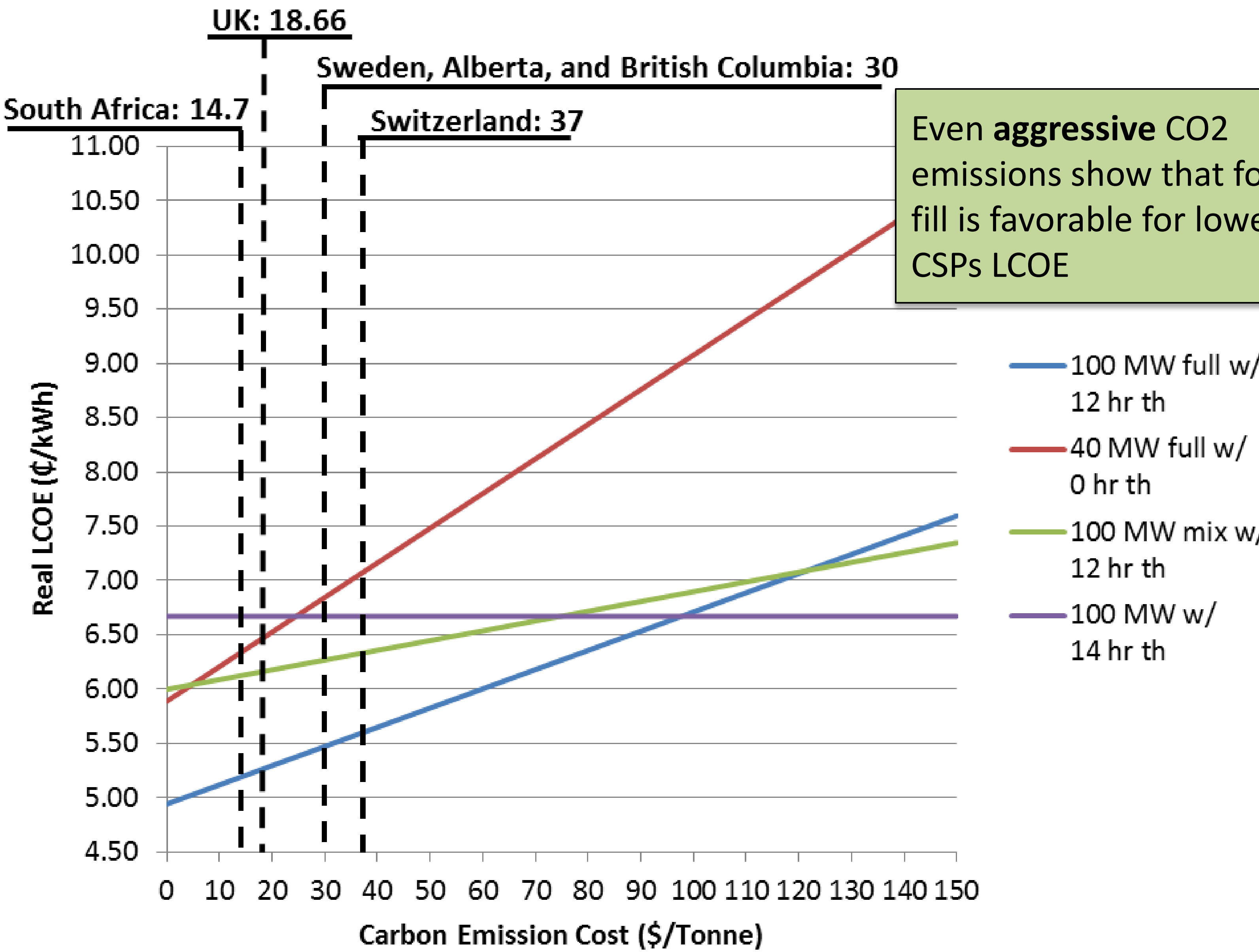


Investigated System Models

- Four plant configurations were found having a good combination of solar output and LCOE

Size (MW)	100	40	100	100
Annual generation (MWh)	768,037	310,815	550,754	454,993
Annual operation time	99.87%	99.69%	74.16%	63.18%
Percent power from fossil	36.52%	66.10%	18.09%	0.00%
Thermal storage (hrs)	12	0	12	14
Fossil fill	All Day/All Year	All Day/All Year	Daytime/Summer	None
Fossil backup cost ($/kW)	50	50	50	0
Power block cost ($/kW)	800	925	800	800
Real LCOE (¢/kWh)	**4.95**	**5.90**	**6.00**	**6.67**
Nominal LCOE (¢/kWh)	6.80	8.10	8.24	9.16
Annual fuel use (MMBTU)	1,899,547	562,362	966,168	0
Annual CO_2 emitted (kg/MWh)	181.5	328.0	93.0	0
Average Ambient Temp. (°C)	19.9	19.9	22.9	23.4

LCOE vs. Carbon Tax

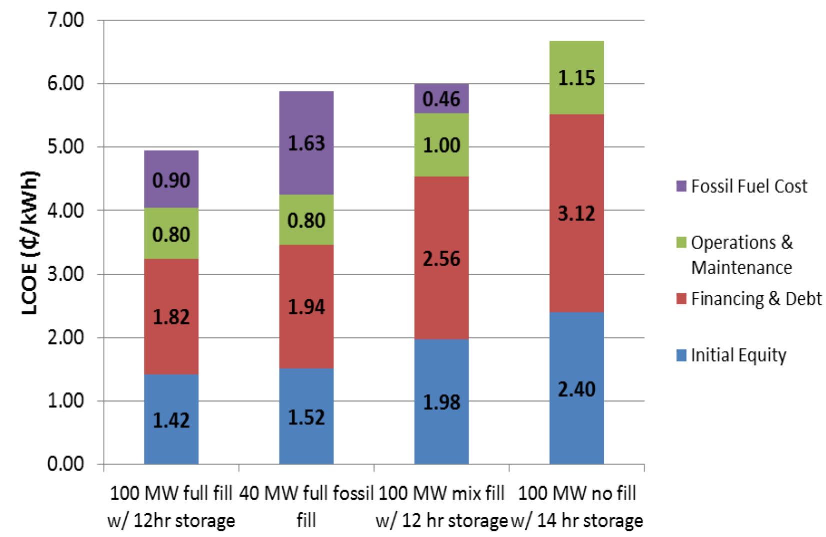


Even **aggressive** CO2 emissions show that fossil fill is favorable for lowering CSPs LCOE

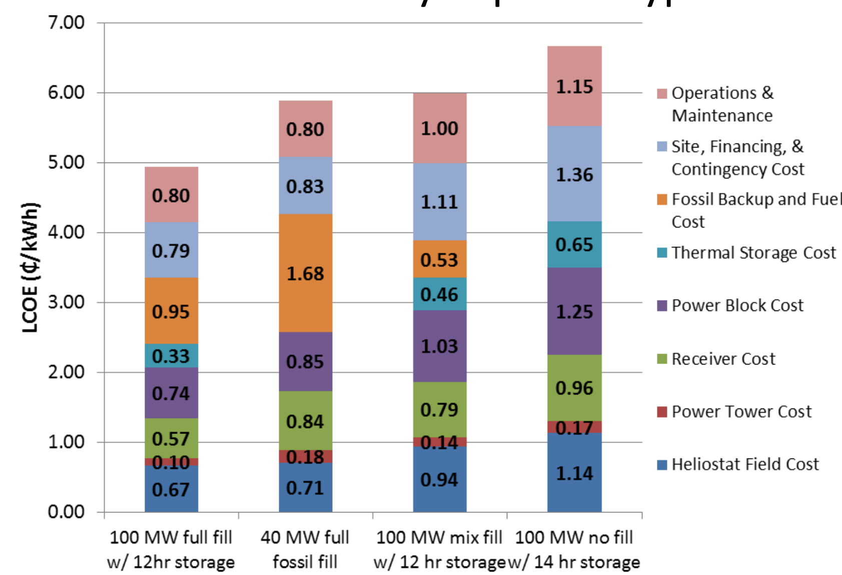
Real LCOE trends for changes in carbon tax

Breakdown of LCOE

- Although fuel and O&M costs increase with fossil fill, the relative $/kWh decreases substantially because more electricity is produced each year.
- Adding fossil fill does not require new technology, current quotes have been procured for similar equipment under the STEP initiative.



LCOE Breakdown by Expense Type



LCOE Breakdown by System Cost

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