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

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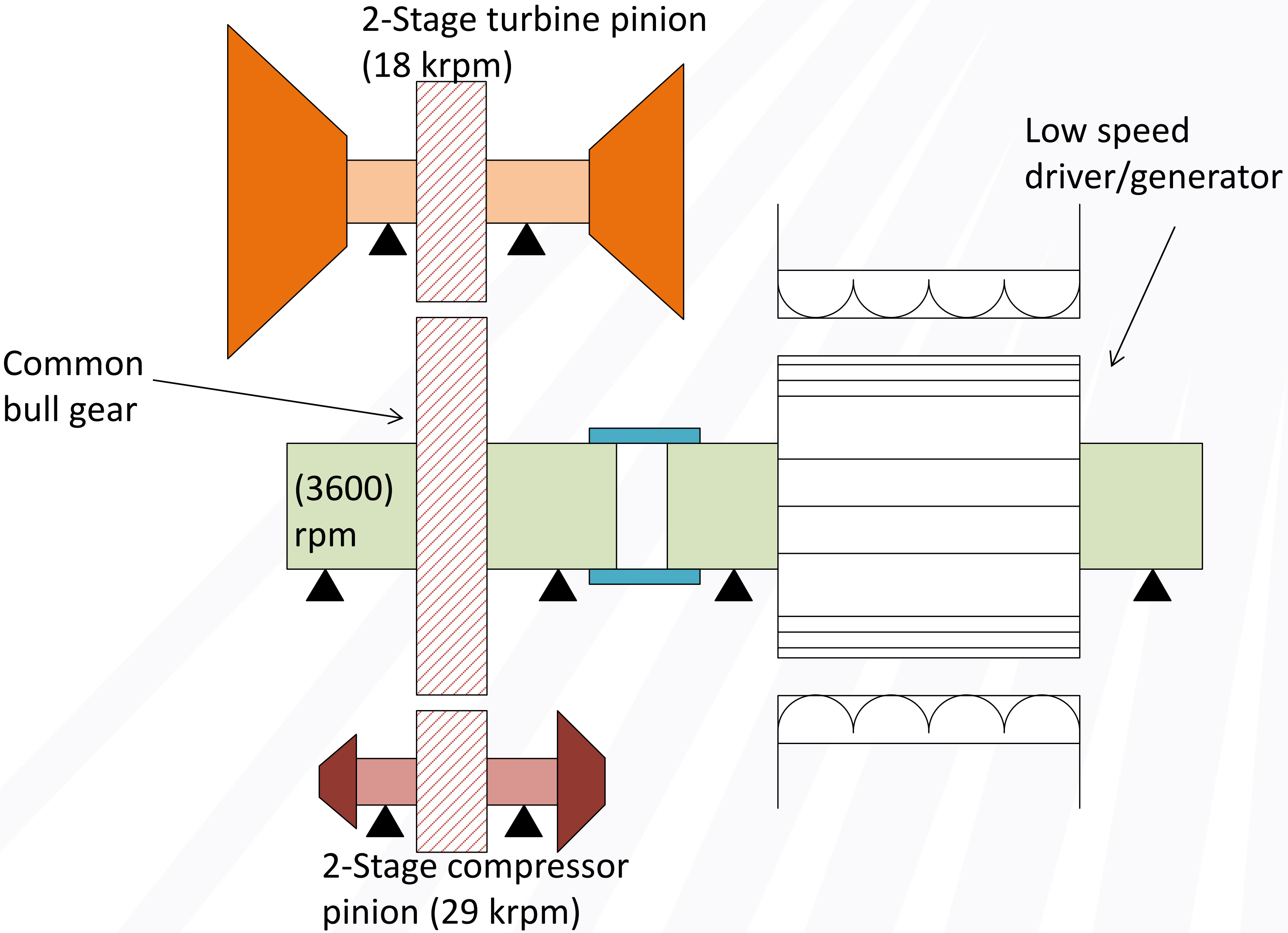
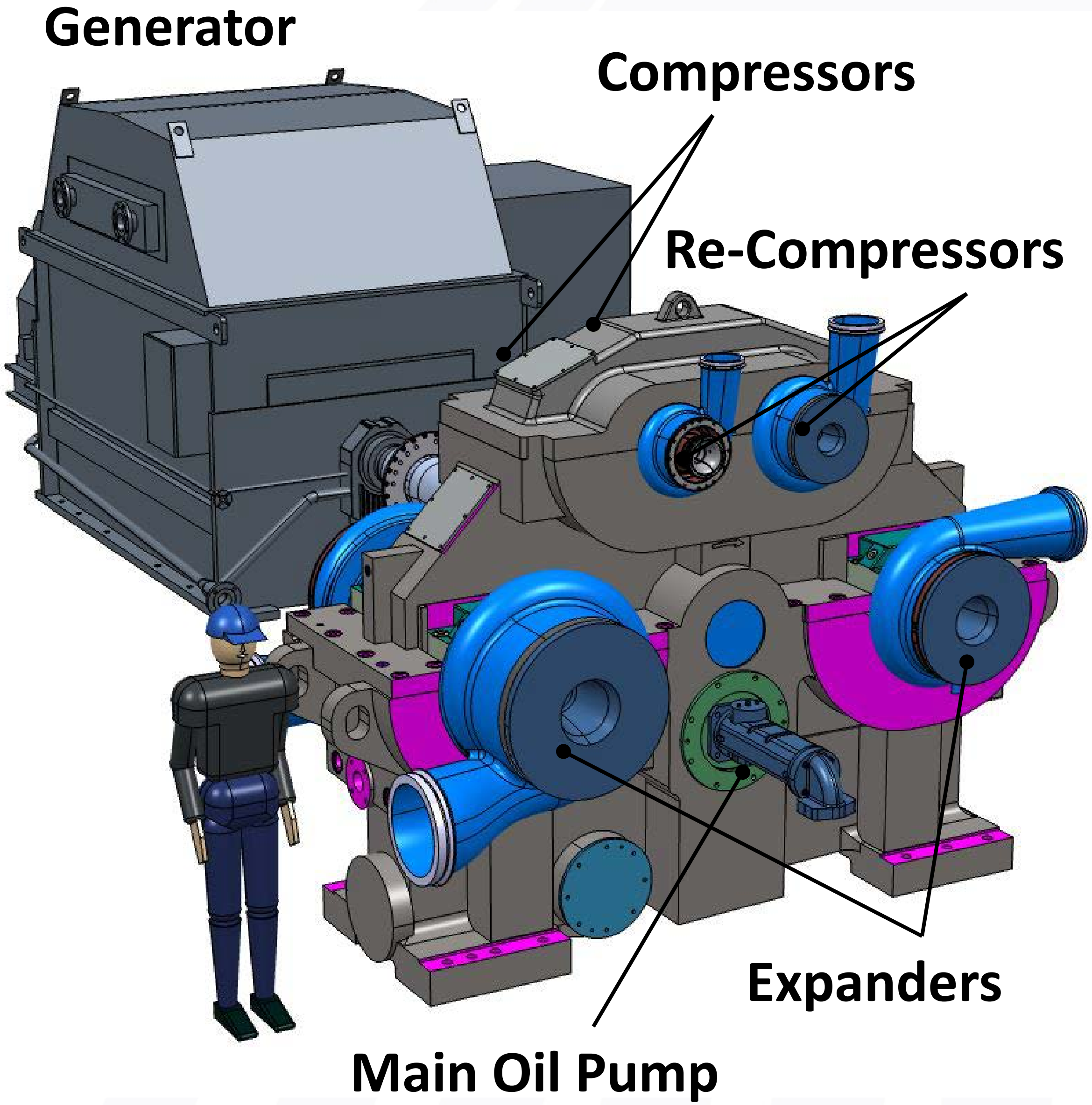
An integrally geared compander is composed of pinions having compressors and turbines geared to a common shaft



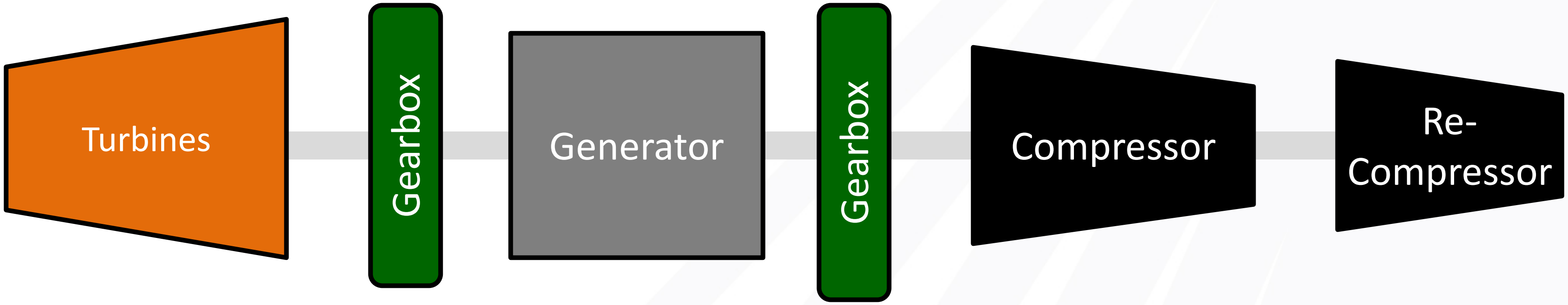
An IGC allows for an interesting power block concept for S-CO2 Brayton cycles and alternative cycles

- 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

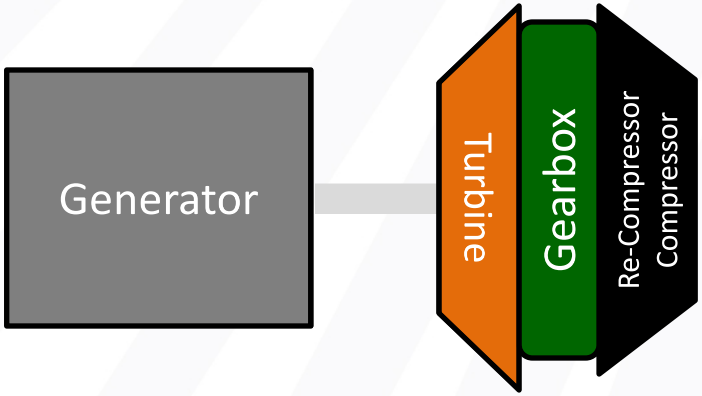


An IGC package incorporates all the key elements of a conventional train in a compact modular package

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)

Project objectives and key milestones

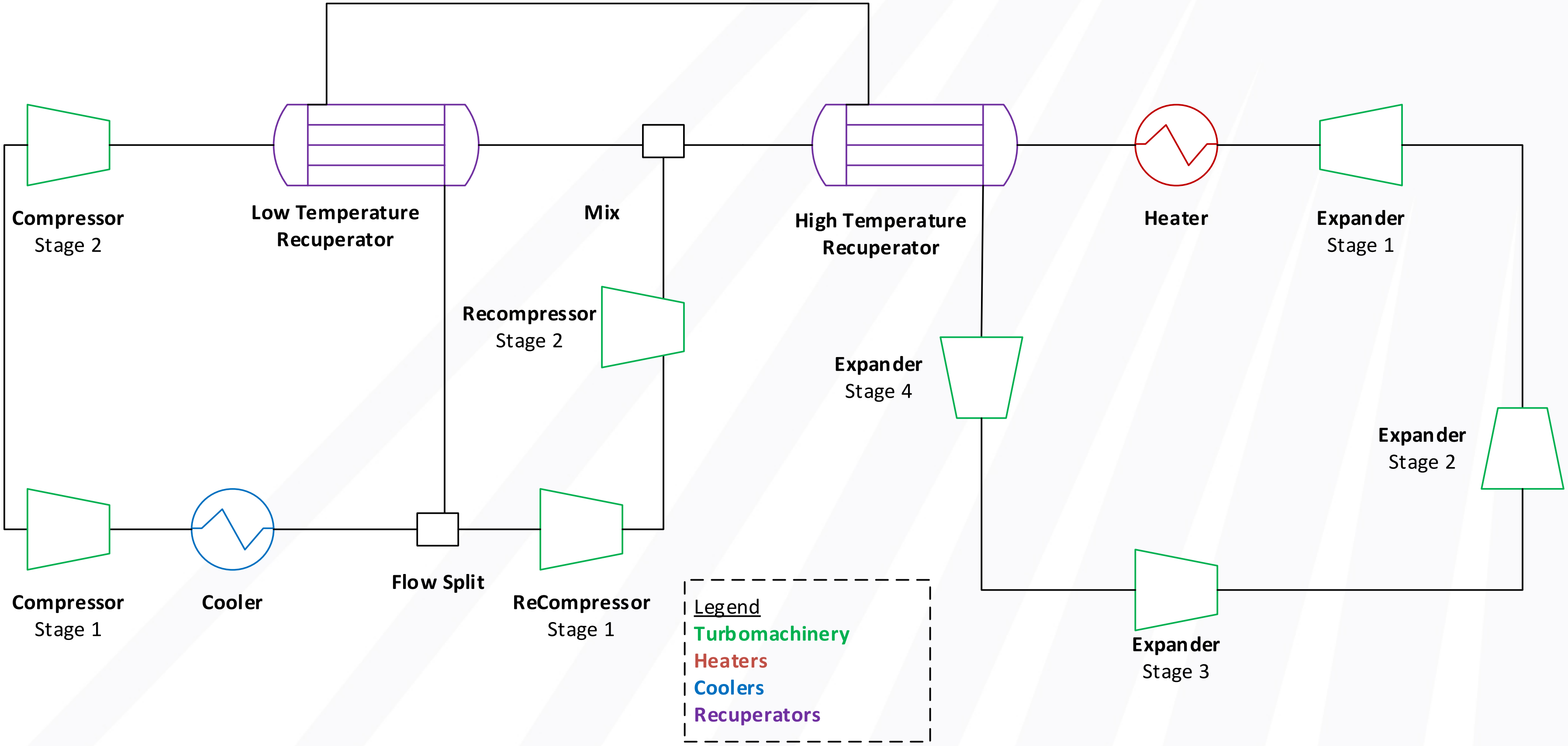
- Design a 10 MW_e cycle using a compander as the power block (targeting 50% at design point)
- Investigate off-design cycle operation, wide-range compression capabilities, and control schemes of an IGC based power block
- Design a reduced flow IGC to be tested in SwRI's 1 MW_e test loop.
  - Full flow wide-range compressor (50-70% range)
  - Reduced flow expander (705°C inlet temperature)
  - Full frame core (900\$/kW_e, 6¢/kW_e LCOE)
- Test the unit at full temperature and pressure

Work has been divided into three project phases

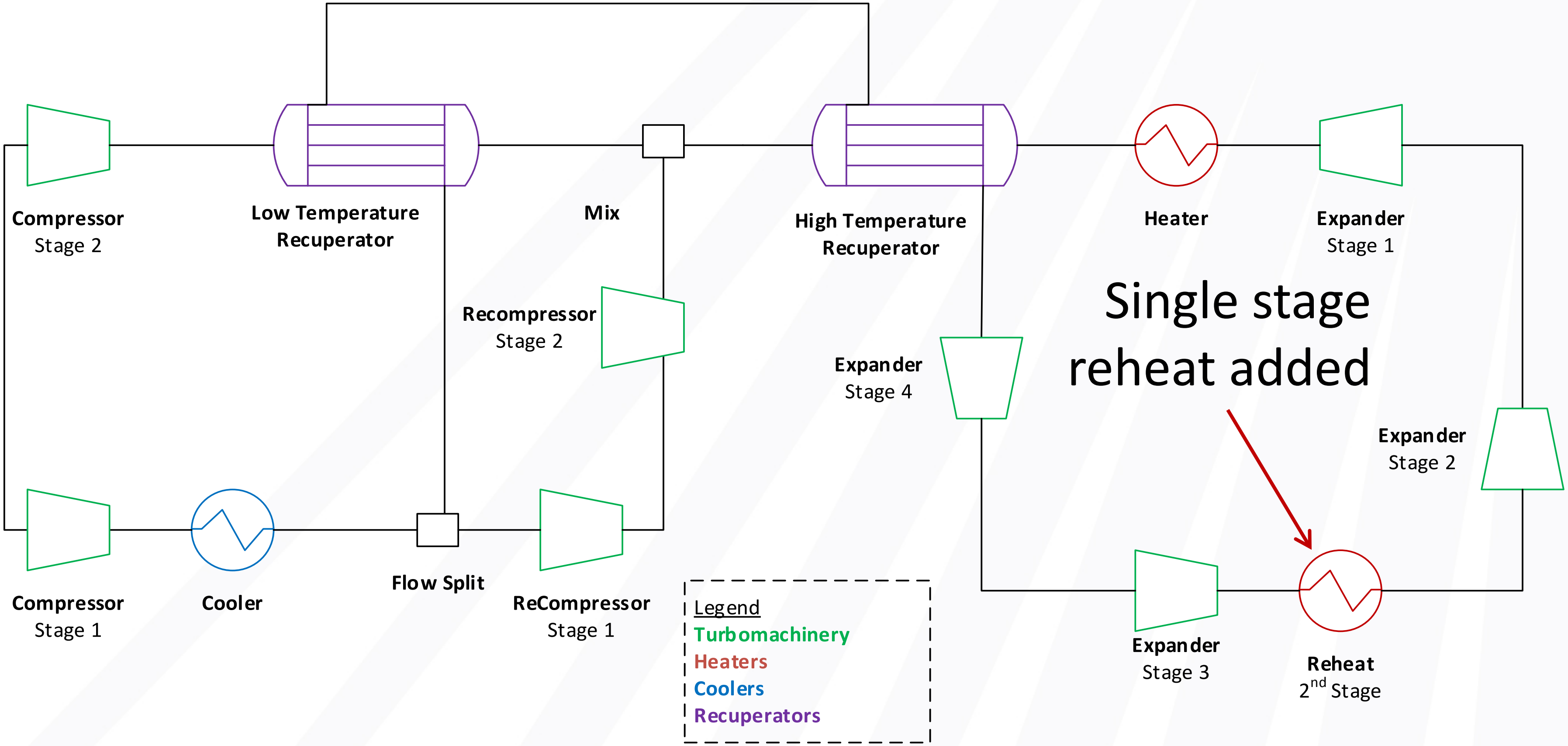
- Phase I – Cycle modeling, turbomachinery and loop design
- Phase II – IGC fabrication and loop construction
- Phase III – Loop and IGC commissioning and full pressure and temperature testing

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

Conventional recompression cycle



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



Compressor Stage 2

Low Temperature Recuperator

Mix

High Temperature Recuperator

Heater

Expander Stage 1

Recompressor Stage 2

Expander Stage 4

Single stage reheat added

Expander Stage 2

Compressor Stage 1

Cooler

Flow Split

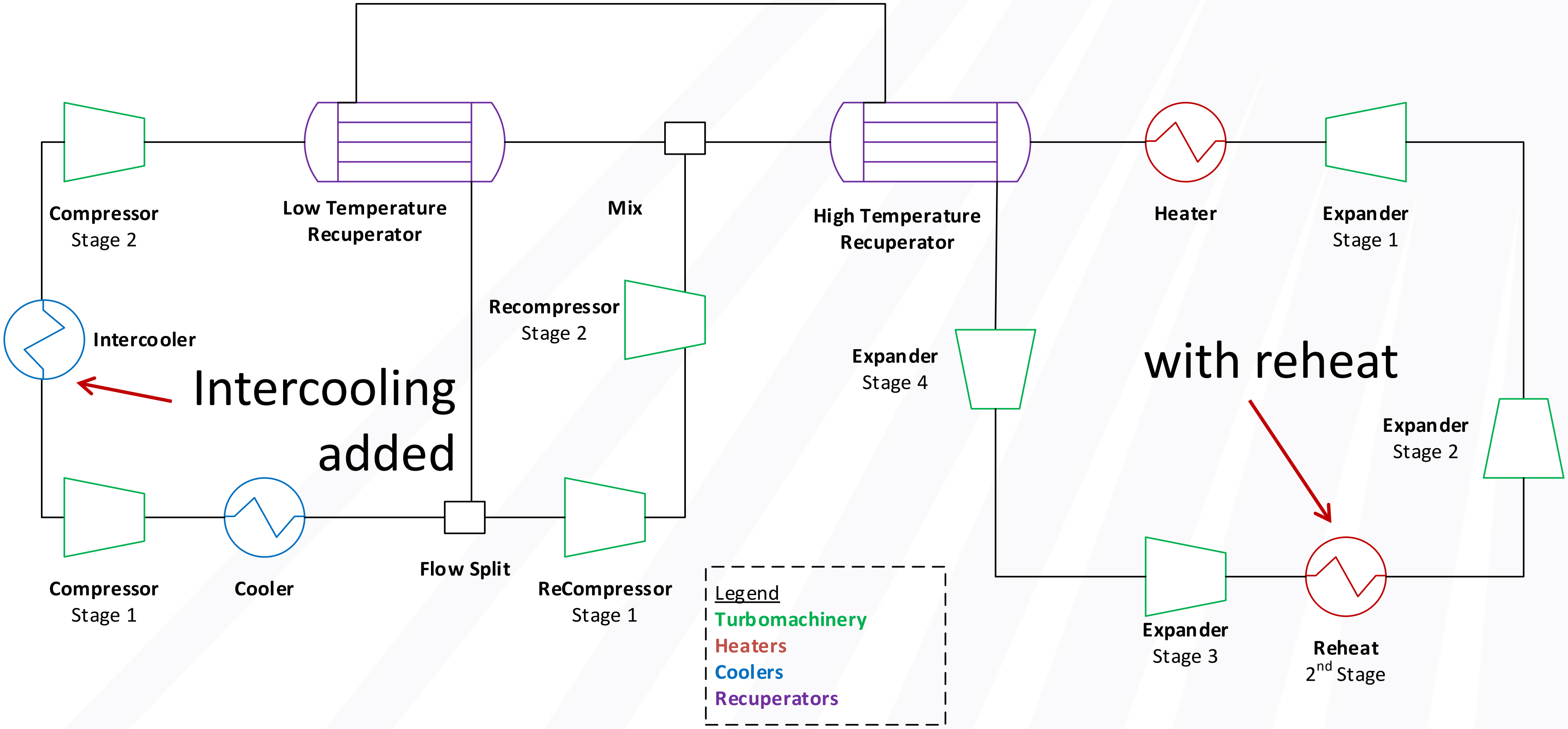
ReCompressor Stage 1

Expander Stage 3

Reheat 2nd Stage

Legend
- **Turbomachinery**
- **Heaters**
- **Coolers**
- **Recuperators**

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



Compressor Stage 2

Low Temperature Recuperator

Mix

High Temperature Recuperator

Heater

Expander Stage 1

Intercooler

Intercooling added

Recompressor Stage 2

Expander Stage 4

with reheat

Expander Stage 2

Compressor Stage 1

Cooler

Flow Split

ReCompressor Stage 1

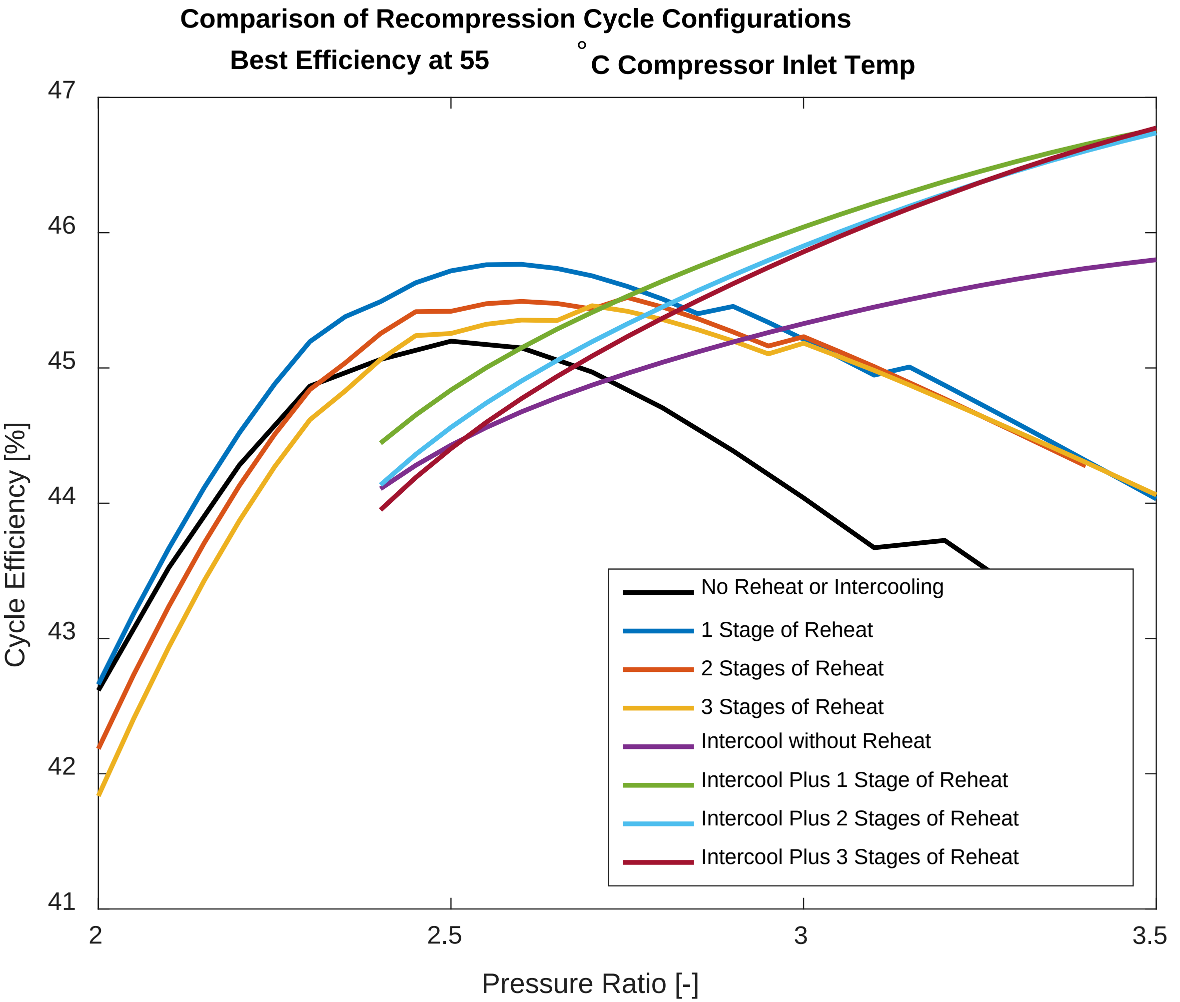
Expander Stage 3

Reheat 2nd Stage

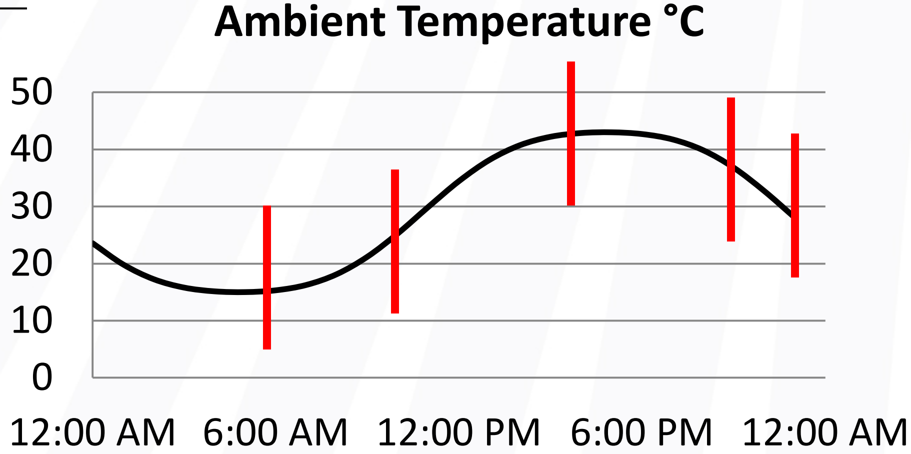
Legend
- **Turbomachinery**
- **Heaters**
- **Coolers**
- **Recuperators**

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

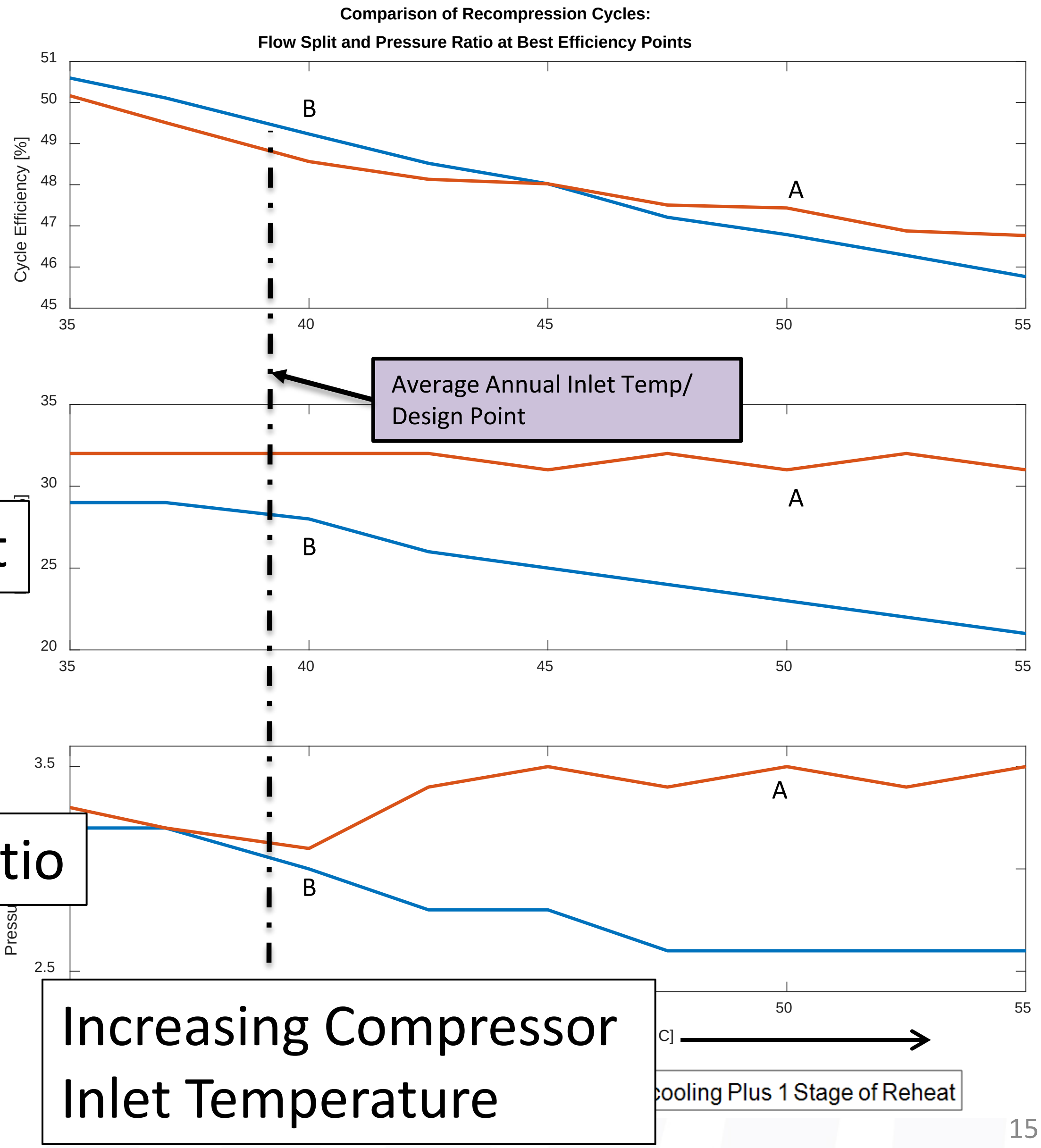


The transient challenges of a concentrated solar power plant are significant



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 cyc are more efficient on hot days, and less efficient on cool days

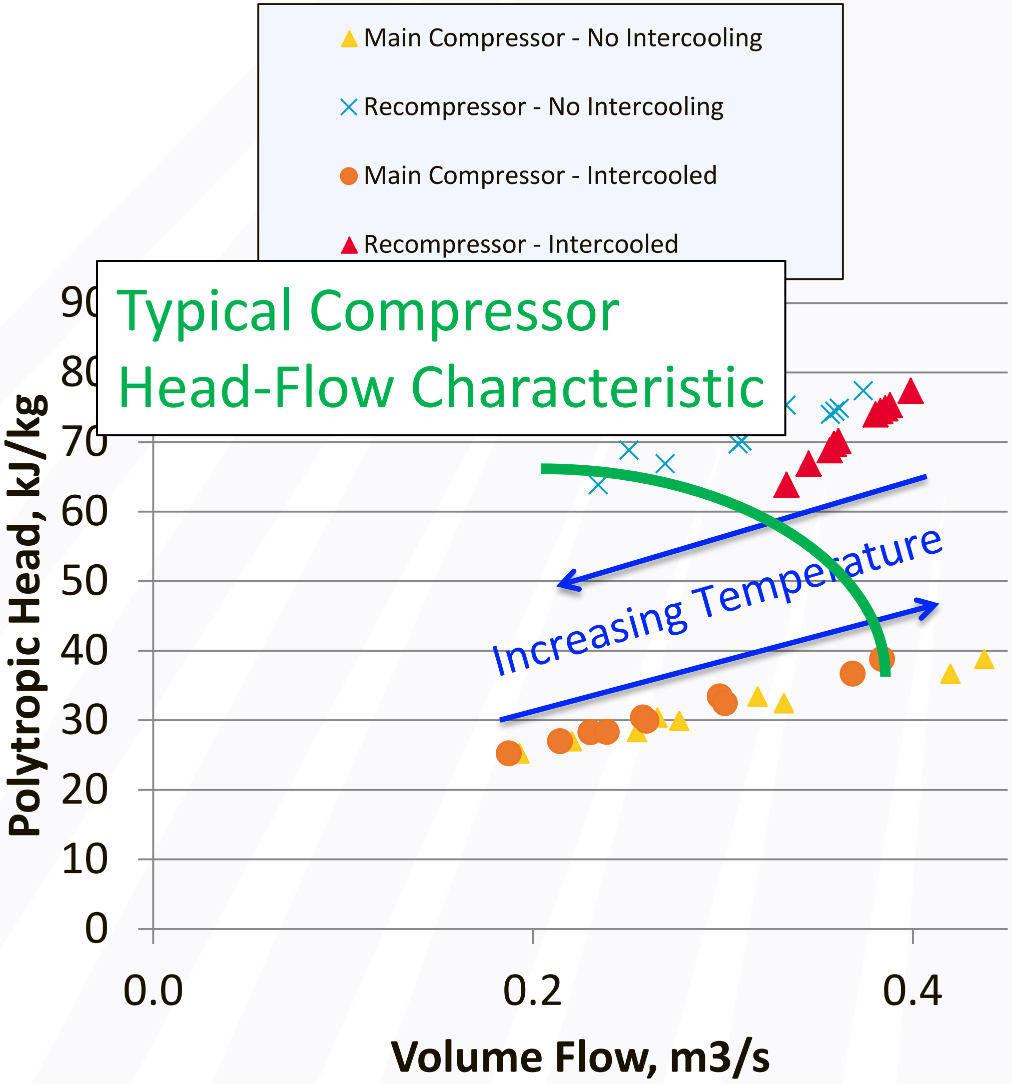


Average Annual Inlet Temp/ Design Point

Increasing Compressor Inlet Temperature

Wide-Range impeller operation is essential to optimizing cycle efficiency

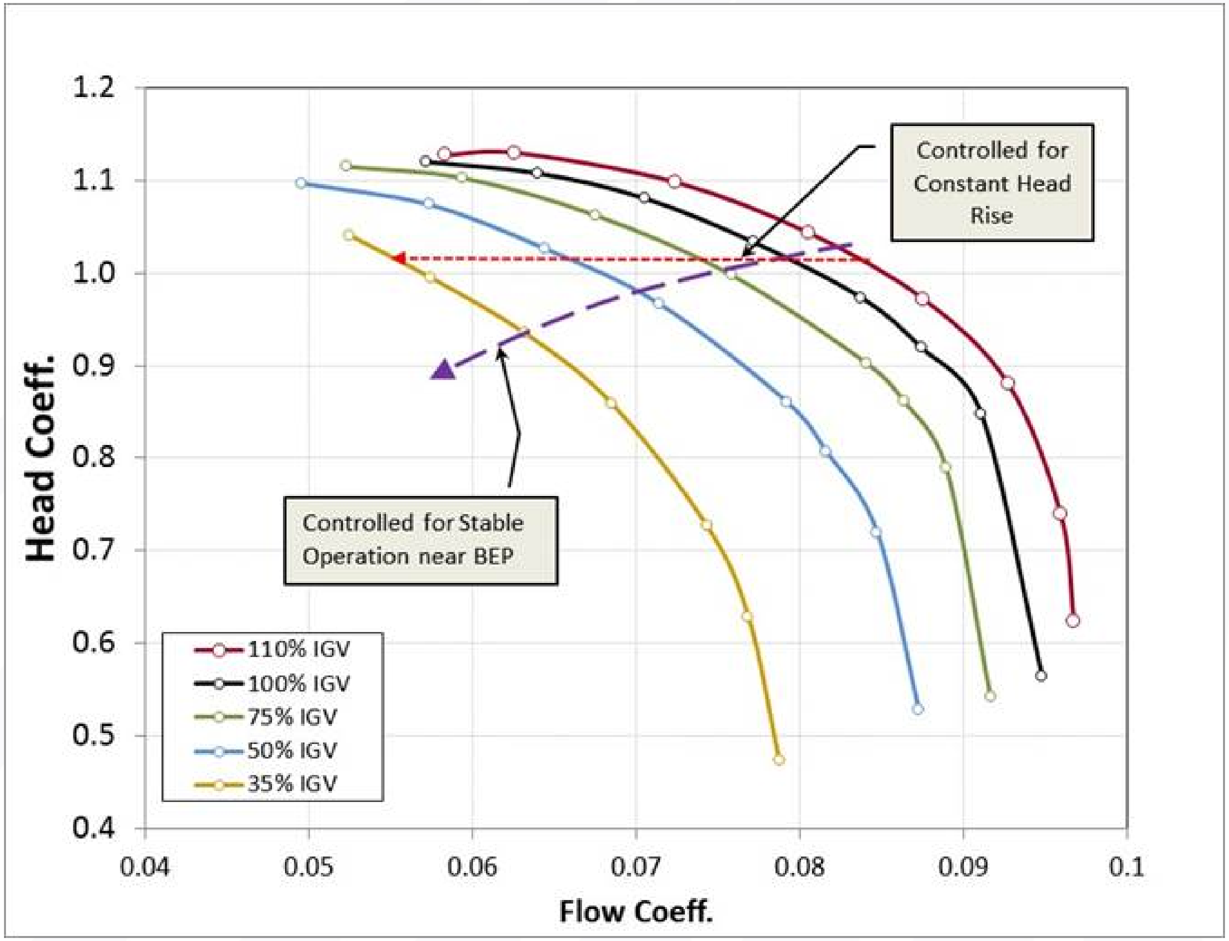
- Range Requirements at Optimal Efficiency Condition (without using range reduction techniques)
  - Compressor > 55%
  - Recompressor > 37%
- Control Strategies
  - Alter flow split and pressure ratio to reduce compressor requirements
  - Control compressor inlet temperature
  - Employ inlet guide vanes



Typical Compressor Head-Flow Characteristic

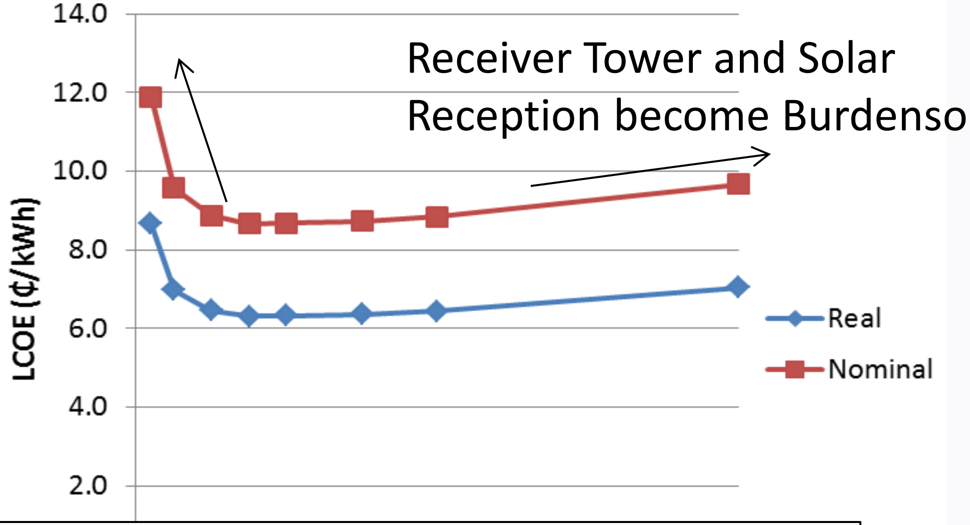
IGVs may be essential to maximize off-design efficiency for varying compressor inlet temperatures

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



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 and expected F



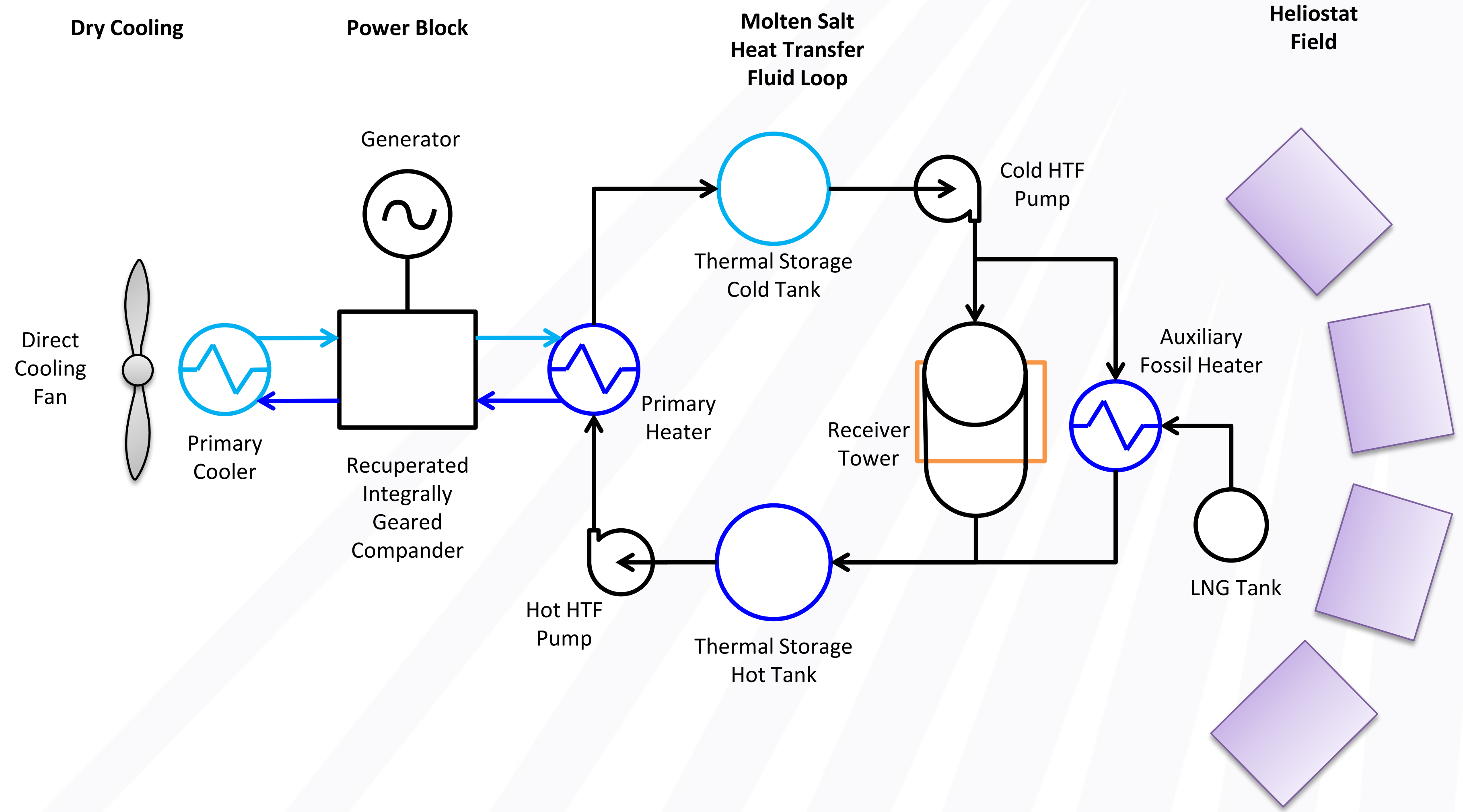
Cap-ex/Produced Power Excessive

Receiver Tower and Solar Reception become Burdensome

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



Investigated system models show promising trends with fossil assist

- 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

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