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A Practical Look at Assumptions and Constraints for Steady State Modeling of sCO_2 Brayton Power Cycles

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Introduction

- **Recent interest in sCO_2 cycles has led to a large number of systems modeling studies for a variety of heat sources**
- **Cycle configurations are still being optimized with respect to:**
  - Heating and cooling sources being utilized
  - Overall plant economics for commercialization
  - Development of cycle components for larger scales and more severe operating conditions
- **Need for consistency in techno-economic sCO_2 cycle studies**
  - Ease of comparison between sCO_2 cycle arrangements, and against competing cycles (e.g. steam)
  - Minimize effects of unrelated technologies on sCO_2 plant performance
- **Assumptions and constraints for steady-state modeling and techno-economic analyses are recommended to allow for more meaningful results and comparisons**
  - Based on NETL's and EPRI's collective expertise, and role as collectors and clearinghouses of sCO_2 power cycle information
  - Conference paper intended to be a living document – please correct us!

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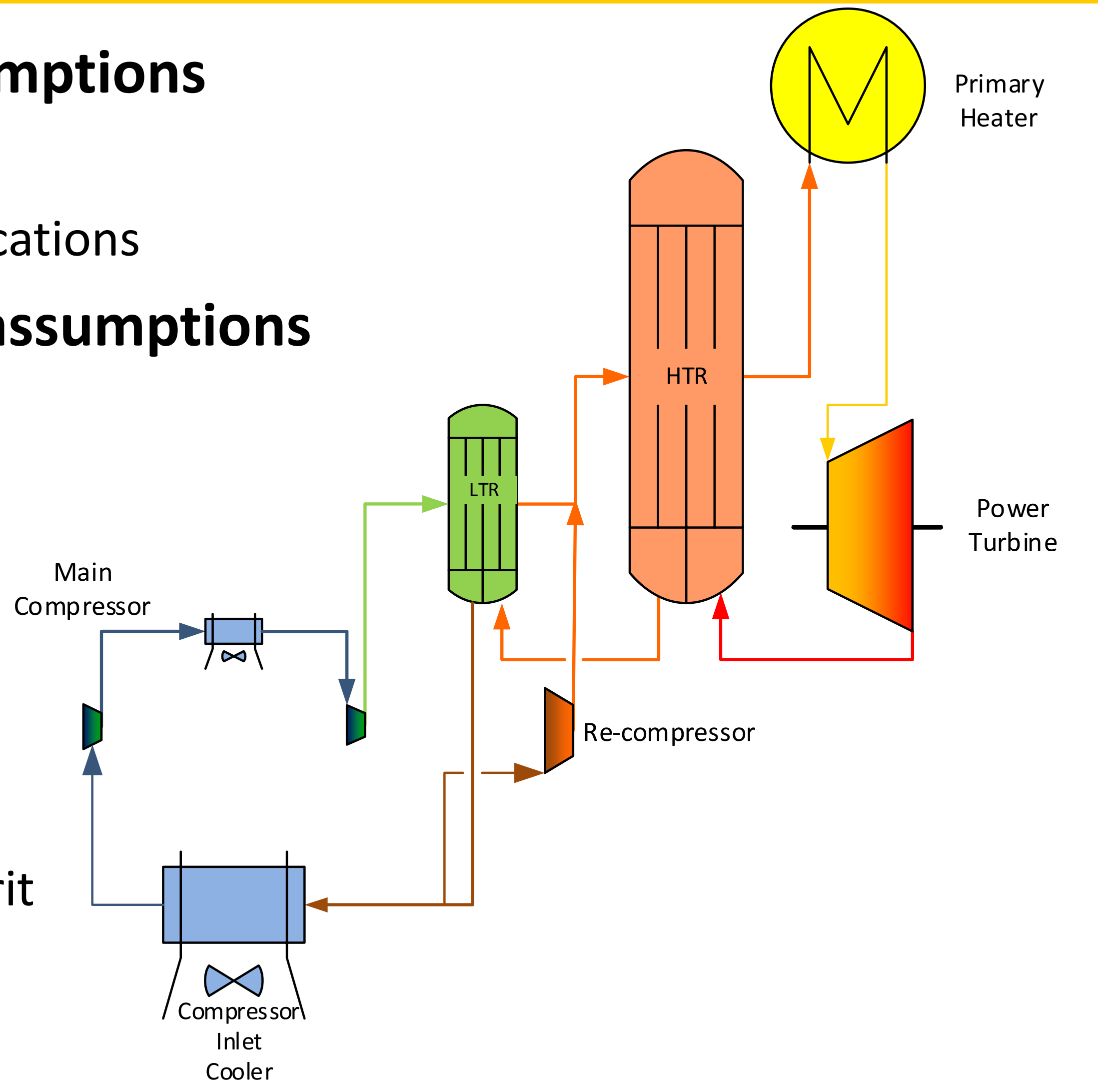
Presentation Outline

- **General Technical Assumptions**
  - Ambient environment
  - Fuel/heat source specifications
- **Power cycle modeling assumptions**
  - Turbomachinery
  - Heat exchangers
  - Other equipment and assumptions
- **Economic modeling**
  - Capital cost estimates
  - Economic Figures of Merit



Ambient Environment

- **A nominal plant location should be specified**
  - Daily and seasonal ambient conditions affect plant performance
  - Location and environment affect economics
- **Representative sites from NETL and EPRI studies:**

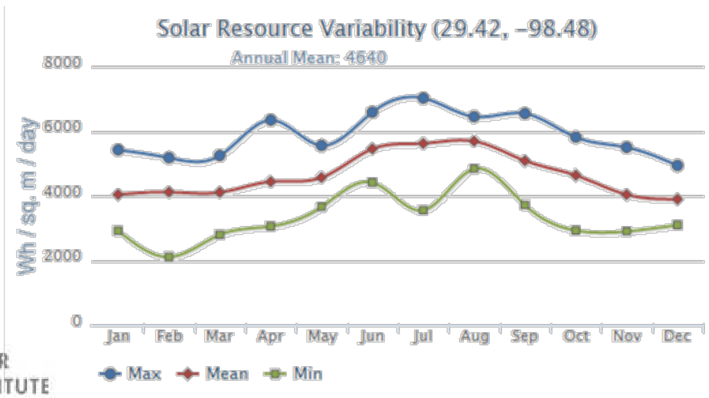
Site Conditions	Montana	Midwest ISO	Kenosha, WI
Elevation, m (ft)	1,036 (3,400)	0 (0)	184 (604)
Barometric Pressure, MPa (psia)	0.090 (13.0)	0.101 (14.7)	0.0993 (14.4)
Average Ambient Dry Bulb Temperature, °C (°F)	5.6 (42)	15 (59)	15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)	2.8 (37)	10.8 (51.5)	13 (55)
Design Ambient Relative Humidity, %	62	60	60
Cooling Water Temperature, °C (°F)	8.9 (48)	15.6 (60)	--

Thermal Energy Source Specifications

- **Coal**
- **Natural Gas**
- **Solar Irradiance**
  - NREL Solar Prospector Tool
- **Waste Heat**
  - Gas turbine exhaust specs
    - Temperature, pressure, mass flow, composition
  - NETL NGCC studies
- **Nuclear?**

Coal	Beulah-Zap		Rosebud PRB		Illinois #6	
Location	Freedom, ND		Montana		Franklin Co., IL	
Rank	Lignite		Sub-bituminous		HV Bituminous	
	As Rec'd.	Dry	As Rec'd.	Dry	As Rec'd.	Dry
Proximate Analysis (weight %)						
Moisture	36.08	0	25.77	0	11.12	0
Ash	9.86	15.43	8.19	11.04	9.70	10.91
Volatile Matter	26.52	41.48	30.34	40.87	34.99	39.37
Fixed Carbon	27.54	43.09	35.70	48.09	44.19	49.72
HHV (kJ/kg)	15,391	24,254	19,920	26,787	27,113	30,506
LHV (kJ/kg)	14,804	23,335	19,195	25,810	26,151	29,444
Ultimate Analysis (weight %)						
Carbon	39.55	61.88	50.07	67.45	63.75	71.72
Hydrogen	2.74	4.29	3.38	4.56	4.50	5.06
Nitrogen	0.63	0.98	0.71	0.96	1.25	1.41
Chlorine	0.00	0.00	0.01	0.01	0.29	0.33
Sulfur	0.63	0.98	0.73	0.98	2.51	2.82
Oxygen	10.51	16.44	11.14	15.01	6.88	7.75

San Antonio Solar Resource
maps.nrel.gov/prospector



Natural Gas	Volume Percentage	
Methane, CH_4	93.1	
Ethane, C_2H_6	3.2	
Propane, C_3H_8	0.7	
n-Butane, C_4H_{10}	0.4	
Carbon Dioxide, CO_2	1.0	
Nitrogen, N_2	1.6	
Total	100.0	
	LHV	HHV
MJ/scm (Btu/scf)	34.71 (932)	38.46 (1033)
kJ/kg (Btu/lb)	47,454 (20,419)	52,581 (22,625)

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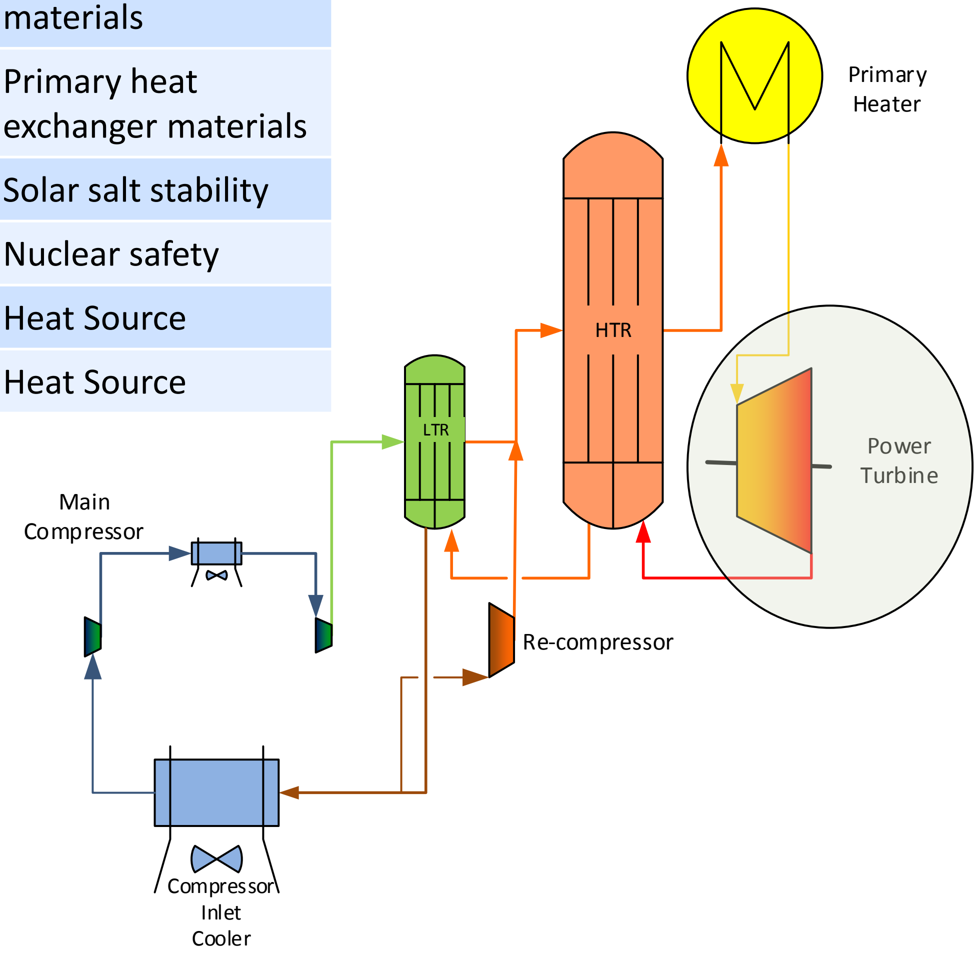
Turbine Model Constraints

Inlet Temperature

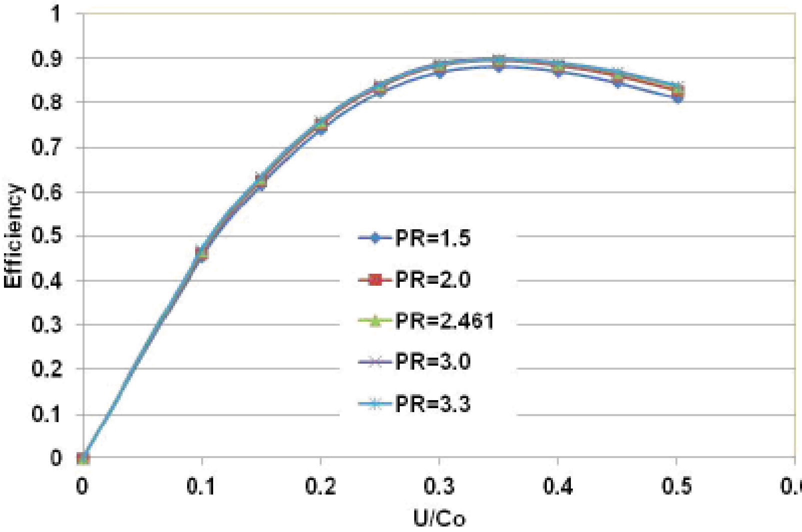
Application	Range (°C)	Recommend (°C)	Limitation
Direct sCO_2	1100 – 1200	1150	Recuperator materials
Indirect Fossil-fueled	600 – 760	700 (near term) 760 (long term)	Primary heat exchanger materials
Solar	550 – 760	700	Solar salt stability
Nuclear	350 – 700	550	Nuclear safety
Waste Heat	< 230 – 650	550	Heat Source
Geothermal	100 – 300	200	Heat Source

- **Inlet temperature dependent on heat source and application**
- **Limiting temperature constraint is *not* the turbine**



Turbine Model Constraints
Other parameters

- **Inlet Pressure: Maximum of 35 MPa (5000 psi)**
  - Consider effect on wall thickness for expensive materials
- **Isentropic Efficiency: Function of size, speed, and type**
  - Recommend 85% for radial turbines <30 MW
  - Recommend 90% for axial turbines >30 MW
- **Part Load Performance**
  - Useful for off-design studies
- **Outlet Conditions**
  - Temperatures affect recuperator materials and cost
  - Pressures affect recuperator flow passage size/pressure drop



Program on Technology Innovation: Modified Brayton Cycle for Use in Coal-Fired Power Plants. EPRI, Palo Alto, CA: 2013. 1026811.

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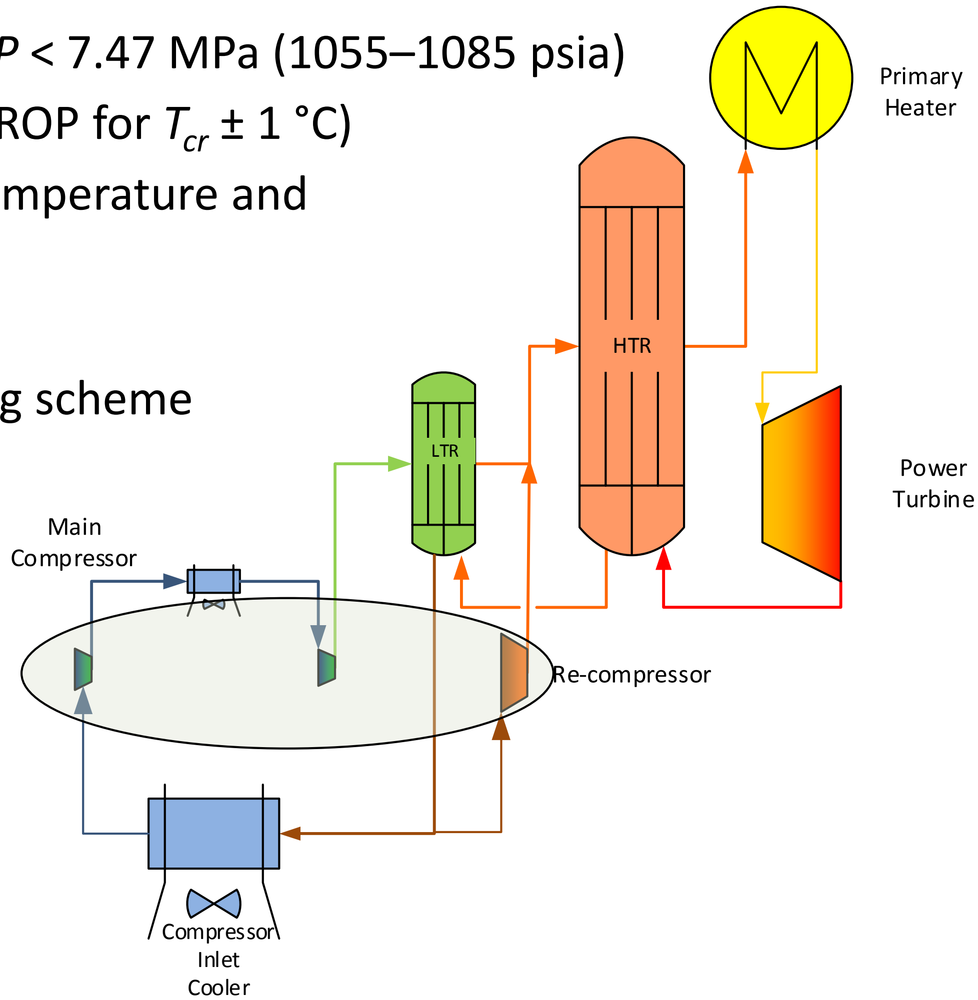
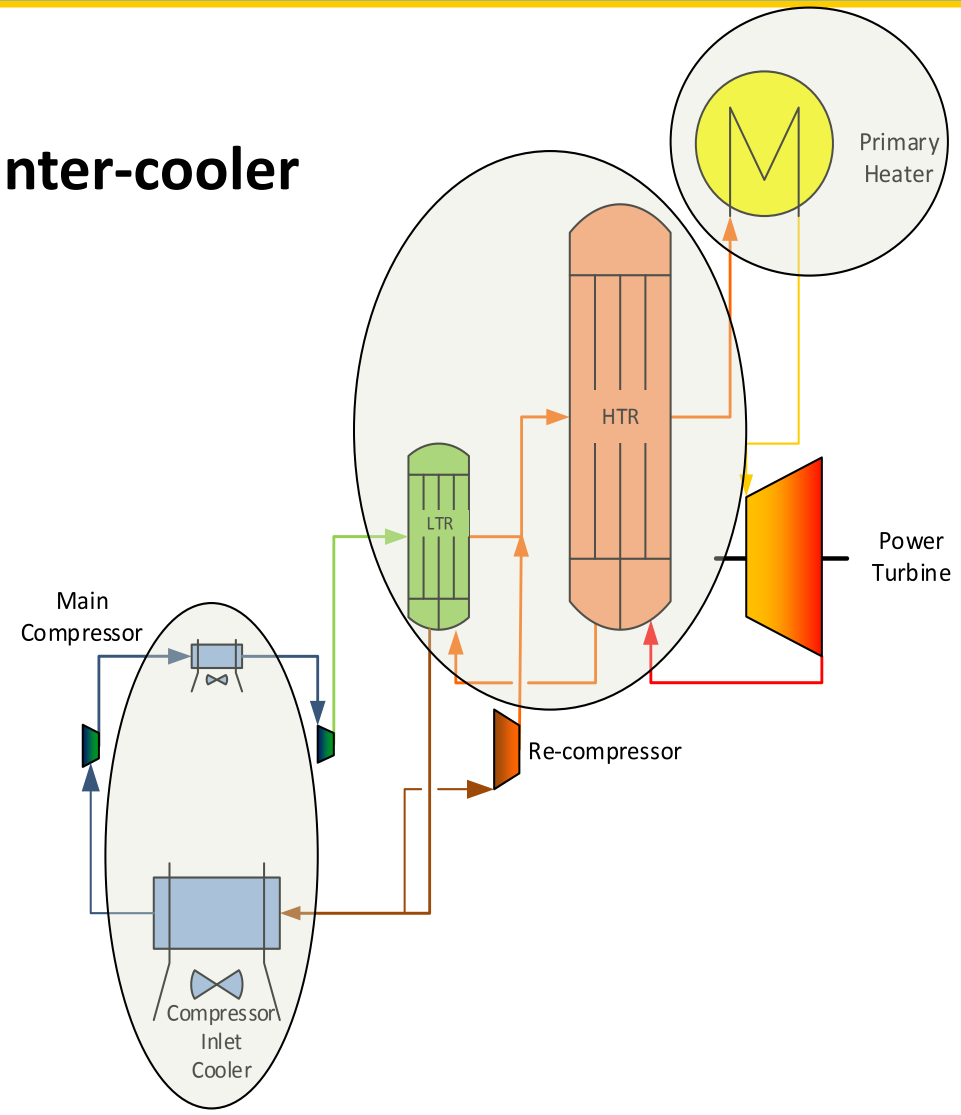
Compressor Model Constraints

- **Avoid critical point regime**
  - 30 < T < 32 °C (86–90 °F), 7.27 < P < 7.47 MPa (1055–1085 psia)
  - sCO_2 property uncertainty (REFPROP for T_{cr} ± 1 °C)
  - Large property variations with temperature and pressure perturbations
- **Inlet Temperature:**
  - Minimum achievable with cooling scheme
- **Inlet Pressure:**
  - Optimal pressure increases with inlet temperature
- **Isentropic Efficiency: Recommend 85%**
- **Part Load Performance: Similar to turbines**



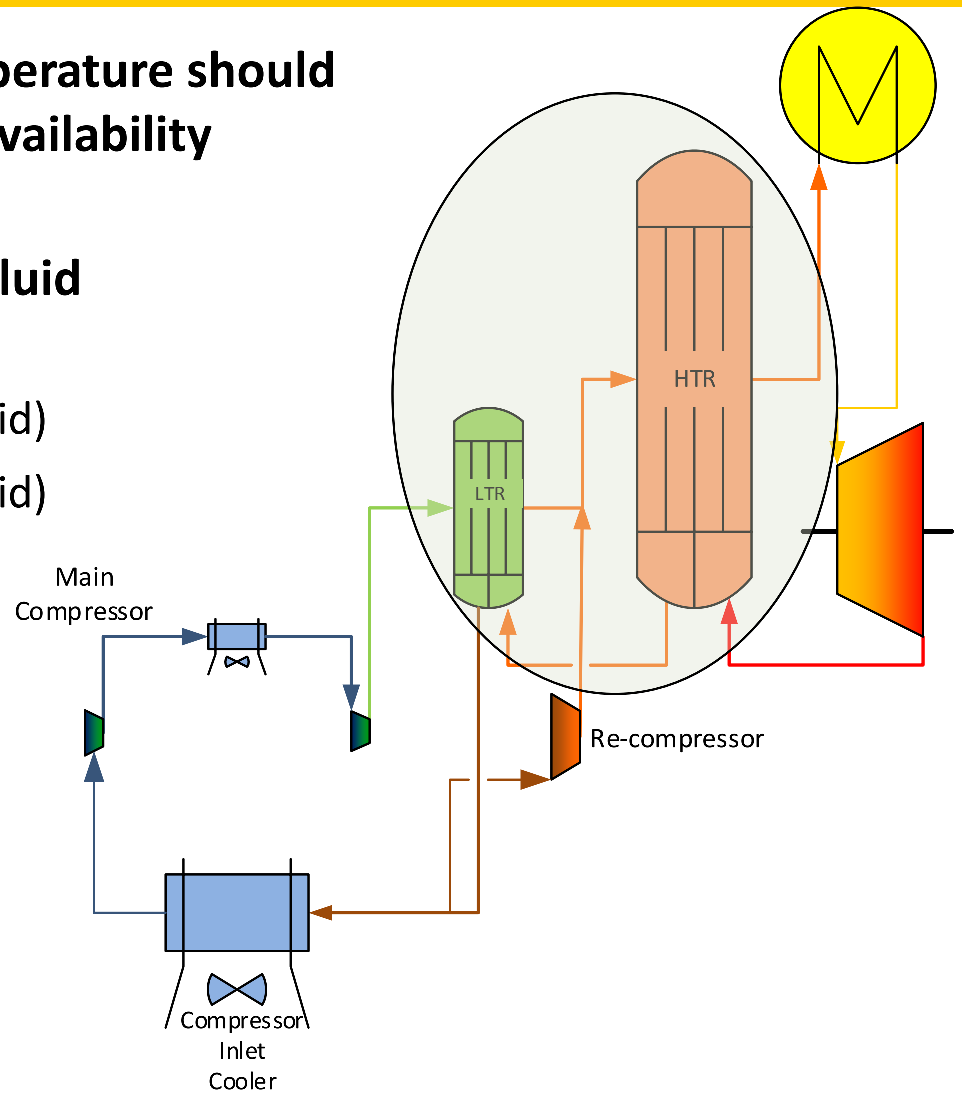
Modeling Heat Exchangers

- **Recuperators**
- **Compressor Inlet Cooler / Inter-cooler**
- **Primary Heater**



Recuperator Model Constraints
Temperature, Pressure Drop

- **<u>Temperature</u> – No recuperator temperature should exceed 760 °C (1400 °F) limited by availability of structural alloys.**
- **<u>Pressure Drop</u> – Lacking a detailed fluid flow model inside the recuperator:**
  - High P (cold) side: 140 kPa (20 psid)
  - Low P (hot) side: 240 kPa (40 psid)



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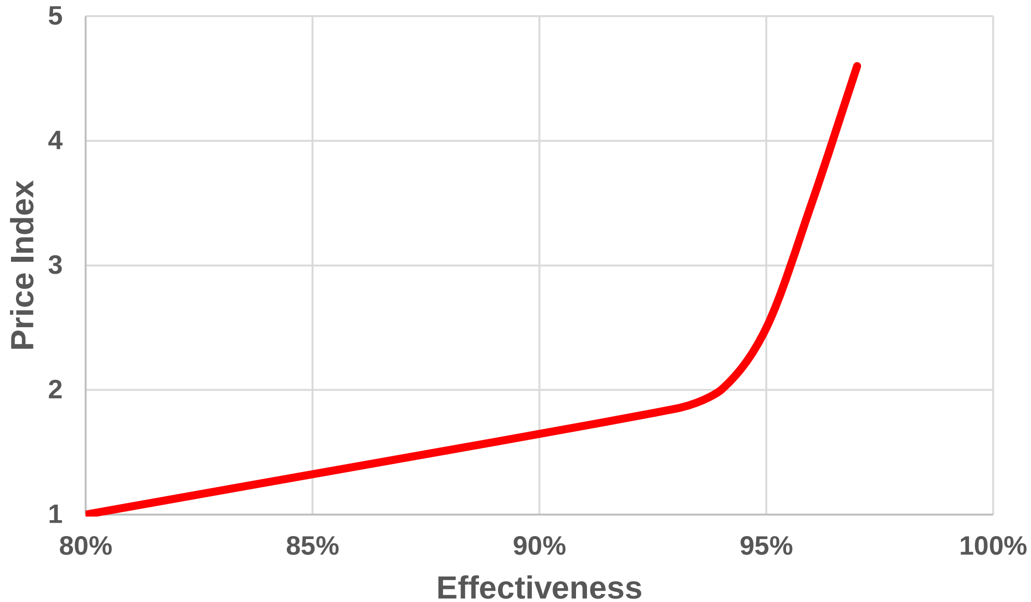
Recuperator Model Constraints
Heat Transfer Performance

The primary constraint on heat exchanger performance is cost. Cost rises quickly as specified effectiveness rises above 80% and very quickly as specified effectiveness rises above about 93%.

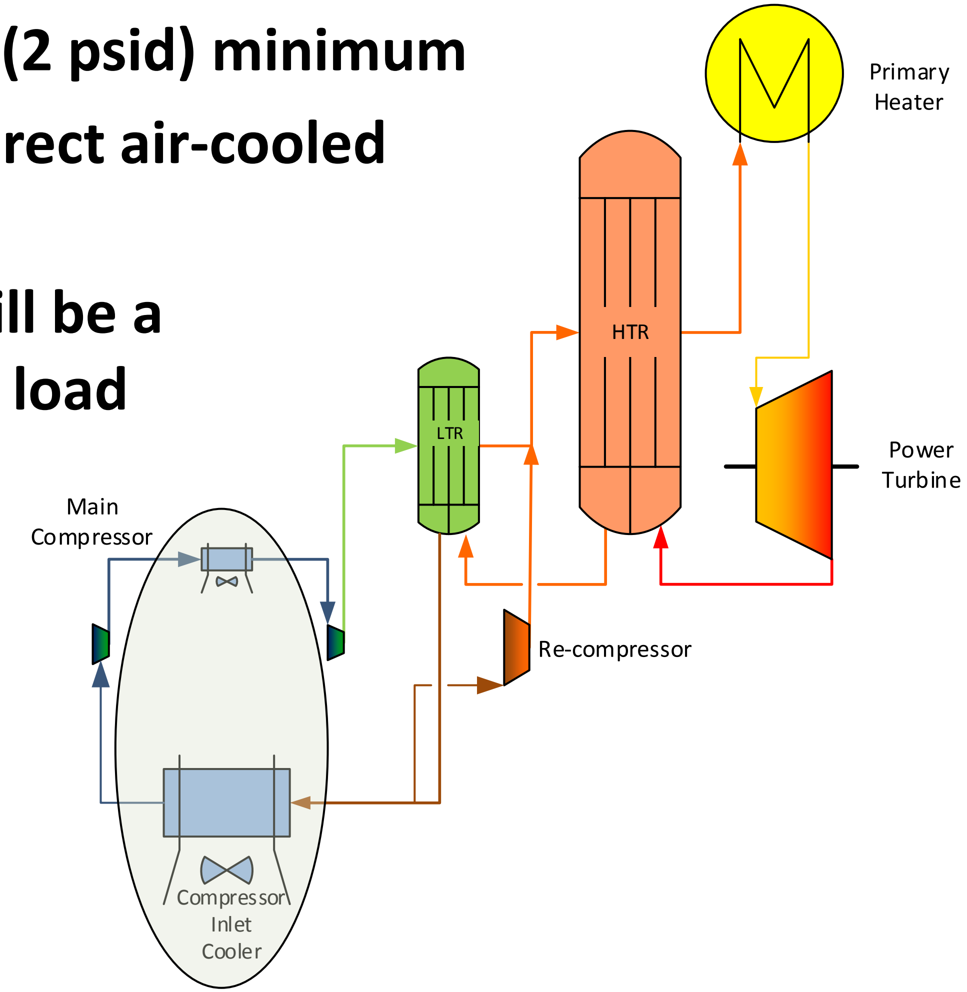
- **Detailing the relationship between recuperator cost and performance will be critical to sCO_2 Brayton cycle development.**
- **In practice, recuperator effectiveness greater than 90% may not be justified.**
- **In any event, cost justification should be provided for recuperator effectiveness greater than about 93%.**



Compressor Inlet Cooler / Intercoolers

Pressure Drop:

- **CO_2 pressure drop: 15 kPa (2 psid) minimum**
- **Include piping losses for direct air-cooled coolers**
- **Cold-side pressure drop will be a significant auxiliary power load**



Compressor Inlet Cooler / Intercooler
Heat Transfer Performance

- **As with recuperators, cost will constrain inlet cooler and intercooler performance. For now, rely on steam-cycle power plant experience.**
- **Performance will also be constrained by ambient conditions. Lacking specific weather data:**

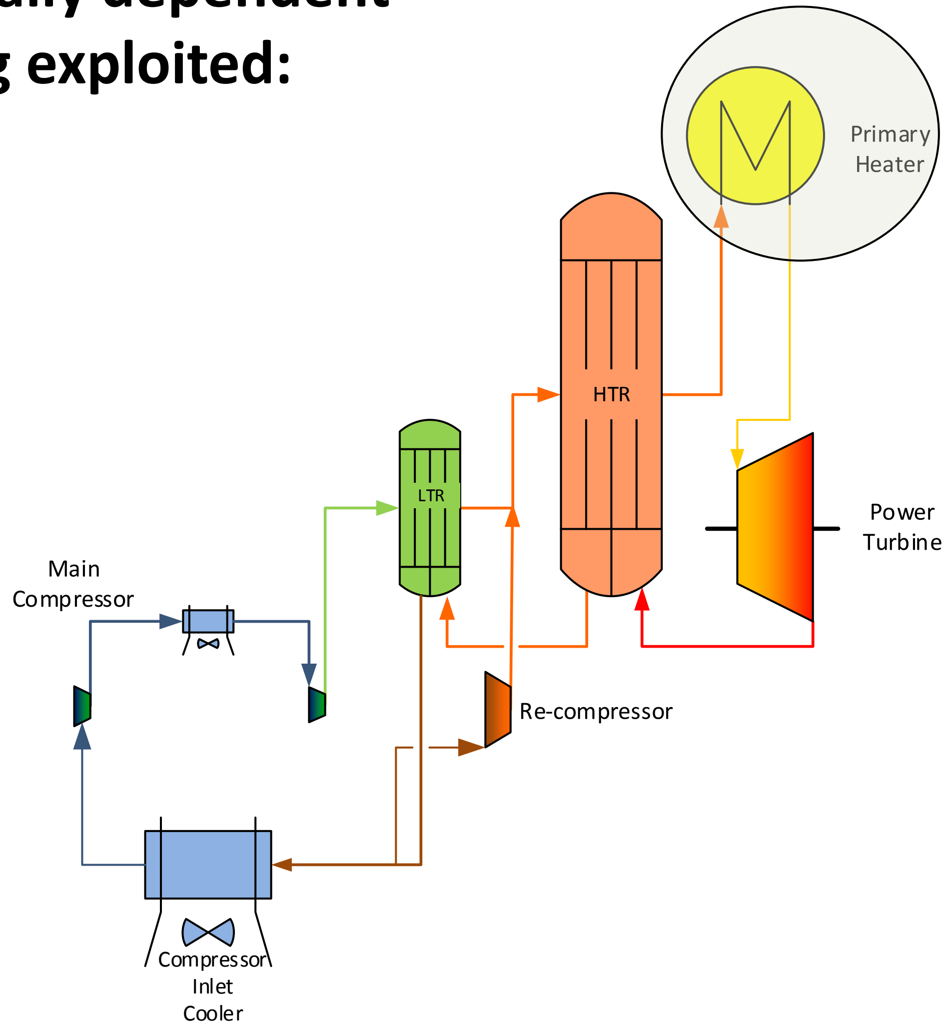
Cooling System Type	Coolant Supply Temperature	Coolant Approach	Cold-side Aux. Power (per MWth duty)
Water-cooling wet cooling tower	32°C (90°F)	8 °C (13°F)	Mech. Draft: 16 kWe Nat. Draft: 10 kWe
Water-cooling dry cooling tower	43°C (110°F)	8 °C (13°F)	Mech. Draft: 16 kWe Nat. Draft: 10 kWe
Hybrid wet/dry	37°C (100°F)	8 °C (13°F)	Mech. Draft: 16 kWe Nat. Draft: 10 kWe
Once-through water cooling	21°C (70°F) North Sea: 5°C (39°F)	8 °C (13°F)	9 kWe
Direct, air-cooling	Ambient dry bulb	15 °C (28°F)	Mech. Draft: 30 kWe

Additional work is needed to analyze cycle cost/performance vs. coolant approach temperature.

Primary Heater

Primary heater design is critically dependent on the thermal resource being exploited:

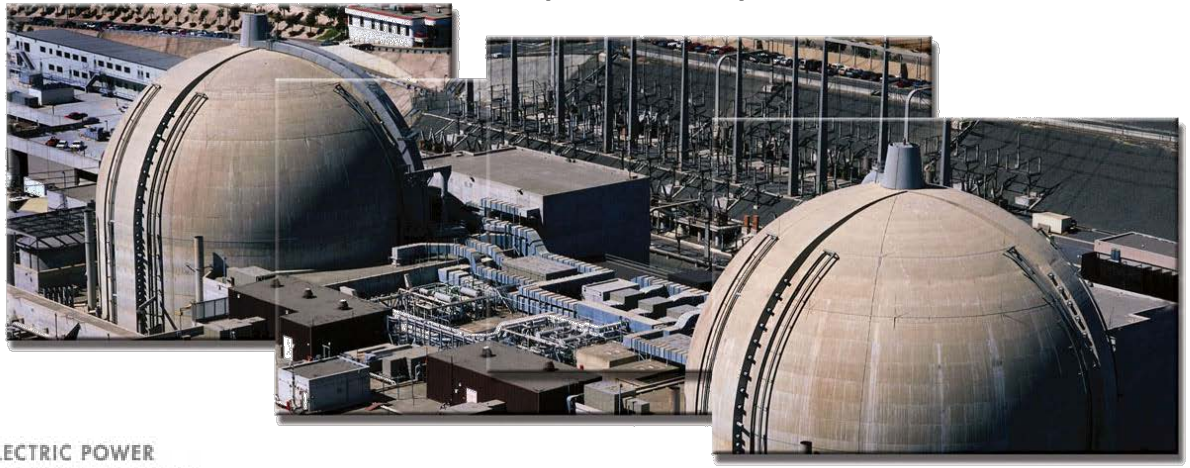
- **Nuclear**
- **Solar**
- **Fuel-fired**
- **“Waste” Heat**



Nuclear

Reactor coolant to sCO_2 heat exchanger is very similar to the high temperature recuperator. Lacking a specific primary heater model:

- Pressure drop: 200 kPa (30 psid)
- Effectiveness: 90%, no greater than 93%
- Temperature: Metal temperature no greater than 760°C (1400°F)



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Solar

Model will generally use specific heat flux/coolant temperature

- **Pressure drop:** **200 kPa (30 psid)**
- **Effectiveness:** **Not applicable to model assumptions**
- **Temperature** **Metal temperature no greater than 760°C (1400°F)**

Fuel-fired and "Waste" Heat

Meaningful results will require some detail in the primary heater design. Much of the thermal resource is at a temperature less than 540°C (1000°F), the temperature range where recuperation also occurs.

- **Fuel-fired pressure drop (lacking a detailed fired heater design):**
  - 700 kPa (100 psid) minimum
  - 3400 kPa (500 psid) conservative
- **"Waste" heat sCO_2 pressure drop**
  - 200 kPa (30 psid)
- **Temperature:**
  - no metal temperatures should exceed 760°C (1400°F)
- **Gas-side to sCO_2 temperature difference (for heat transfer):**
  - 28°C (50°F) minimum
  - 55°F (100°F) conservative
- **Minimum gas-side temperatures:**
  - 120°C (250°F) natural gas and low-sulfur fuels
  - 150°C (300°F) sulfur-containing flue gas
- **There will be significant auxiliary power loads associated with gas-side pressure drop; typically 2% to 5% of gross power production.**

Interconnecting Piping

Lacking a specific piping design:

- **Pressure Drop:**
  - 3 m (10 ft) 34 kPa (5 psid)
  - 60 m (200 ft) 345 kPa (50 psid)
- **Temperature drop**
  - 3°C (5°F)
- **Temperature**
  - no metal temperatures to exceed 760°C (1400°F)

Performance Metrics and Balance of Plant

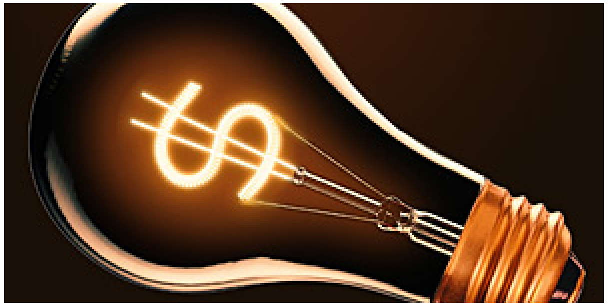
- **Net sCO_2 *cycle* efficiency must include other cycle losses:**
  - Generator: recommend 98.5% conversion efficiency
  - Gearbox (required below ~100 MWe): recommend 99% efficiency
  - Drive Motor (required for compressors if not turbine-driven):
    - Recommended efficiency:

95%	< 1 MWe
96.5%	1 – 10 MWe
97%	> 10 MWe

- **Net *plant* efficiency must include other auxiliary plant loads beyond those required for the sCO_2 cycle**
  - Air handlers, cooling systems (covered earlier), fuel handling, etc.
  - Refer to NETL's Quality Guidelines for Energy Systems Studies as a starting point
- **Primary heater efficiency (fraction of thermal resource delivered to the sCO_2 cycle) should be reported, including heat losses**

Economic Modeling

- **Purpose of the capital cost estimate**
- **Quality of the capital cost estimate**
- **Capital cost nomenclature**
- **Procedures to accumulate costs and calculate cost Figures of Merit**



Purpose of the Capital Cost Estimate

Economic analysis parameters vary with purpose

- **For pilot or demonstration projects:**
  - Include First-of-a-Kind (FOAK) equipment costs
  - Higher process contingencies for scale-up uncertainties
  - Higher financing costs (8-11%) due to increased risk
- **For comparison of sCO_2 plant designs to competing technologies:**
  - Scale process equipment to commercial scale, N^{th}-of-a-Kind (NOAK) costs
  - Process contingencies consistent with mature technologies
  - Lower financing costs (7-9%) after technology risk has been lowered through demonstration

Technology Status	Process Contingency
New Concept – limited data	40+%
Concept with bench scale data	30-70%
Small Pilot scale data	20-35%
Full sized modules tested	5-20%
Commercial process	0-10%

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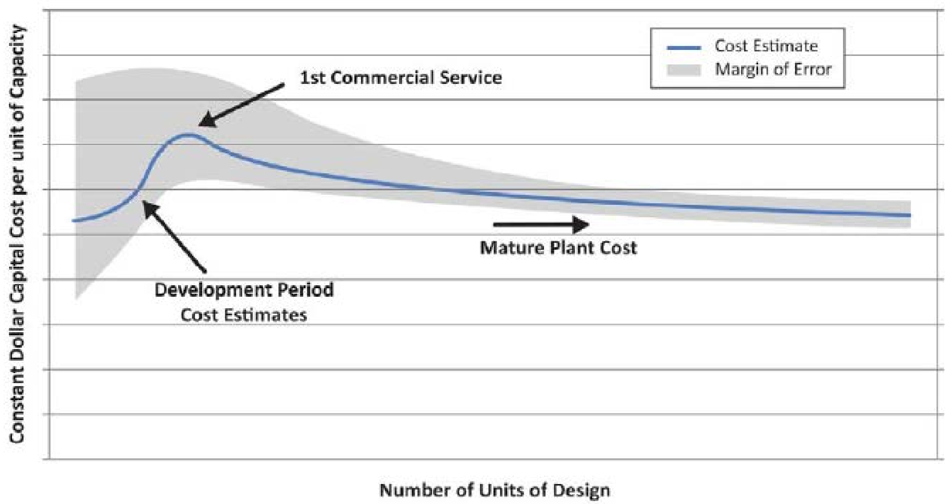

Quality of the Capital Cost Estimate

AACE International Cost Estimate Classifications

Estimate Class	Primary Characteristic	Secondary Characteristic			
	Level of Project Definition	End Usage	Methodology	Expected Accuracy	Preparation Effort Index
Class 5	0% - 2%	Concept screening	Capacity Factored, Parametric Models, Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% - 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4

The cost to conduct a Class 4 cost estimate is typically $200,000 to $700,000.

Capital Cost Nomenclature

Capital Cost Categories	Notes
A. Bare Erected Cost	Total constructed costs of all on-site processing and power production units and facilities that directly support production, to the battery limits.
B. EPC Cost	Engineering and home office costs, overhead, and fees.
C. Contingencies	Costs associated with the uncertainty in general project costs and scale-up
D. Owner's Cost	Pre-paid royalties, land costs, financing costs, initial inventory (fuel, chemicals, catalysts, spares, etc.), pre-production (start-up).
E. IDC/AFUDC, escalation	Cost of financing progress payments to vendors and contractors and increases in costs due to escalation during the construction period.

Capital Cost Accumulations	
Total Plant Cost (TPC)	A + B + C
Total Overnight Cost (TOC)	A + B + C + D
Total Plant Investment	A + B + C + E
Total Capital Required (Total As-Spent Capital, TASC)	A + B + C + D + E

Reporting Economic Figures of Merit

Enterprise cost/benefit categories:

- **Financing costs: Capital costs and financial parameters (debt/equity, debt cost, regulated rate of return, project life, etc.)**
- **Non-fuel operation and Maintenance**
  - Fixed: Operations staffing, insurance, taxes, etc.
  - Variable: Most maintenance (capacity factor-related)
- **Fuel/resource operating costs (capacity factor-related)**
- **The most important benefit parameter is the annual capacity factor**

Typical Figures of Merit:

Levelized Cost of Electricity (LCOE):	**\$/MWh**	**Regulated Utilities**
Cost of Electricity:	**\$/MWh**	**NETL/DOE**
Internal Rate of Return (IRR):	**%/year**	**IPPs**

Cost of Electricity (COE)

$$\mathbf{COE} = \frac{\mathbf{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}}{\mathbf{CF \cdot MWh}}$$

- **Where (all items below are to reported):**
  - COE = Cost of generating electricity*
  - CCF = Capital charge factor (annual financing and capital cost burden)
  - TOC = Total overnight capital
  - OC_{FIX} = Sum of all fixed annual operating costs* (labor, taxes, insurance)
  - OC_{VAR} = Sum of all variable annual operating costs at 100% capacity* (fuel, consumables, waste)
  - CF = Plant capacity factor
  - MWh = Annual net megawatt-hours

Capital Charge Factor	High Risk		Low Risk	
Capital Expenditure Period (years)	3	5	3	5
Investor-owned utility	0.111	0.124	0.105	0.116
Indep. power producer	0.177	0.214	0.149	0.176

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* Escalation consistent with the assumed inflation rate, resulting in constant-dollar levelized costs.

Reporting Economic Figures of Merit

Reported Economic Figures of Merit are often ambiguous or poorly defined.

Pertinent resources for developing and reporting unambiguous, well-defined economic Figures of Merit:

- **Toward a Common Method of Cost Estimation for CO2 Capture and Storage at Fossil Fuel Power Plants. EPRI, Palo Alto, CA: 2013. 3002000176. (Free download.)**
- **Quality Guidelines for Energy Systems Studies. http://www.netl.doe.gov/research/energy-analysis/quality-guidelines**
  - Performing a Techno-Economic Analysis for Power Generation Plants
  - Capital Cost Scaling Methodology
  - Process Modeling Design Parameters
  - Estimating Plant Costs Using Retrofit Difficulty Factors
  - Others

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Conclusions

- **Assumptions and constraints for steady-state modeling and techno-economic analyses are recommended**
  – Intended to produce consistency in techno-economic sCO_2 cycle studies to allow for more meaningful results and comparisons against competing cycles
- **Relies heavily on NETL and EPRI standard practices**
  – Additional techno-economic analysis guidelines available through NETL and EPRI. Refer to conference paper for reference details
- **This is a starting point for a more comprehensive set of assumptions and constraints. Please send feedback from industry and experimental research programs to:**
  – Nathan Weiland: nathan.weiland@netl.doe.gov, (412)386-4649
  – David Thimsen: dthimsen@epri.com, (651) 766-8826

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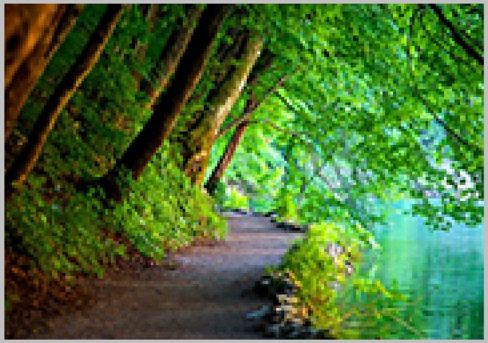

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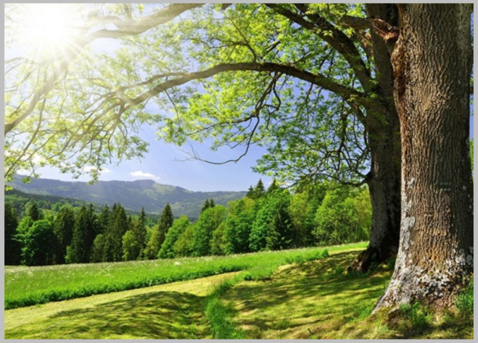

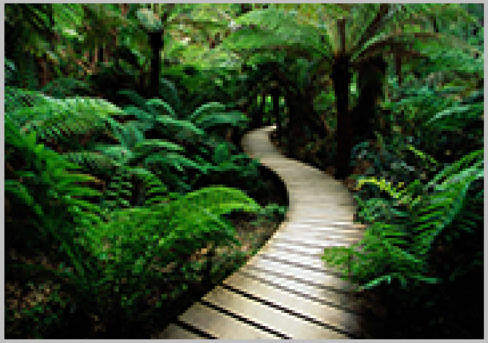

Economic Analysis – COE

- **Cost of electricity (COE) is the revenue a power plant receives for the electricity generated.**
  - An increase in the COE represents an increase in the public's electricity bill
  - Determining the COE is complex set of financial and regulatory rules
  - To simplify the COE calculation, a Capital Charge Factor (CCF) has been developed.
    - Simplifies and unifies common financial terms and assumptions
    - Annualizes the capital cost over the life of the plant
- **A simplified equation can be utilized to determine the COE for Baseline comparison purposes**

$$\mathbf{COE} = \frac{\textit{First year capital charge} + \textit{first year fixed operating costs} + \textit{first year variable operating costs}}{\textit{annual net megawatt hours of power generation}}$$

$$\mathbf{COE} = \frac{\mathbf{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}}{\mathbf{CF \cdot MWh}}$$

Economic Analysis – COE

$$\text{COE} = \frac{\textbf{CCF} \cdot \text{TOC} + \text{OC}_{\text{FIX}} + \textbf{CF} \cdot \text{OC}_{\text{VAR}}}{\textbf{CF} \cdot \textbf{MWh}}$$

Plant Type	CCF w/ CC	CF
PC	0.124	0.85
IGCC	0.124	0.80
NGCC	0.111	0.85

- The **CCF** takes into account the financial aspects of the plant and represents them in a single factor that can then be used to annualize the capital over the life of the plant. Greater detail can be found in the QGESS documents.
- The **MWh** parameter is the net power generated (at 100% CF) by the plant.

Economic Analysis – Capital Costs

$$\text{COE} = \frac{\text{CCF} \cdot \textbf{TOC} + \text{OC}_{\text{FIX}} + \text{CF} \cdot \text{OC}_{\text{VAR}}}{\text{CF} \cdot \text{MWh}}$$

process equipment
supporting facilities
direct and indirect labor
} **BEC**

EPC contractor services
} **EPCC**

process contingency
project contingency
} **TPC**

pre-production costs
inventory capital
financing costs
other owner's costs
} **TOC**

escalation during capital expenditure period
interest on debt during capital expenditure period
} **TASC / TCR**

Bare Erected Cost
Engineering, Procurement and Construction Cost
Total Plant Cost
Total Overnight Cost
Total As-Spent Cost

BEC, EPCC, TPC, TOC and TCR are all "overnight" costs expressed in base-year dollars.

TASC is expressed in mixed-year current dollars, spread over the capital expenditure period.

Capital Costs of process equipment

- **Capital costs for unique equipment may be calculated by several methods:**
  - Scaled: The equipment can be scaled if analogous equipment is available either in an NETL baseline study or otherwise
  - Bottom-up: Build cost from metal and manufacturing cost estimates
  - If neither a scaled approach or a bottom-up estimate can be produced - research goals or bearable costs can be estimated
    - This approach is occasionally used at laboratory scale projects
- **The methodology, reference equipment, and sources of data should be documented in detail within the TEA**
- **Balance of plant will be directly used or scaled from the Baseline reports**

Contingency Estimation

- **Contingency is to cover the known-unknowns or costs that will likely occur based on past experience due to incomplete engineering design**
  - Example: FOAK plant will have high contingencies, the 2nd plant will have lower contingencies but more known costs
- **Two types of contingencies are used:**
  - Process Contingency: intended to compensate for uncertainty in cost estimates caused by performance uncertainties associated with the development status of a technology.
  - Project Contingency: AACE 16R-90 states that project contingency for a "budget-type" estimate (AACE Class 4 or 5) should be 15 percent to 30 percent of the sum of BEC, EPC fees and process contingency.
- **Each "process" in the TEA is assigned a contingency**

Technology Status	Process Contingency
New Concept – limited data	40+%
Concept with bench scale data	30-70%
Small Pilot scale data	20-35%
Full sized modules tested	5-20%
Commercial process	0-10%

Contingency Estimation

- *R&D "projects" should have a higher contingency than those in the Baseline studies*
- *Level of Contingency used should be relative to the development level and engineering completeness of the technology.*

(From NETL's Baseline)

Process Contingency	
Slurry prep and Feed pump	5%
Gasifier and syngas cooler	15%
Two stage Selexol	20%
Mercury Removal	5%
CO_2 removal (PC & NGCC)	20%
Combustion Turbine	5%
AHT in IGCC	10%
Instrumentation and controls	5%

- Process contingencies range between 2-5% of TPC
  (From NETL's Baseline)

- **Contingency is not:**
  - To cover poor engineering or poor estimates
  - Accuracy
  - Cover a scope change
  - Account for delays
  - Unexpected cost escalation
  - Plant performance after startup

Economic Analysis – Operating Costs

$$\text{COE} = \frac{\text{CCF} \cdot \text{TOC} + \mathbf{OC_{FIX}} + \text{CF} \cdot \mathbf{OC_{VAR}}}{\text{CF} \cdot \text{MWh}}$$

Fixed Operating Costs (OC_{FIX})	Variable Operating Costs (OC_{VAR})
Annual Operating Labor Cost	Maintenance Material Cost
Maintenance Labor Cost	**Fuel**
Administrative & Support Labor	Other Consumables
Property Taxes and Insurance	Waste Disposal
Additional OC_{Fix} for new technology	Emission Costs
	Byproduct Revenues
	Additional OC_{Var} for new technology

OC costs reported should be similar to those found in the Baseline Reports

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