Preliminary Benefits of Supercritical CO_2 (SCO_2) Power Cycles

Workshop on SCO_2 Brayton Cycle Energy Conversion R&D

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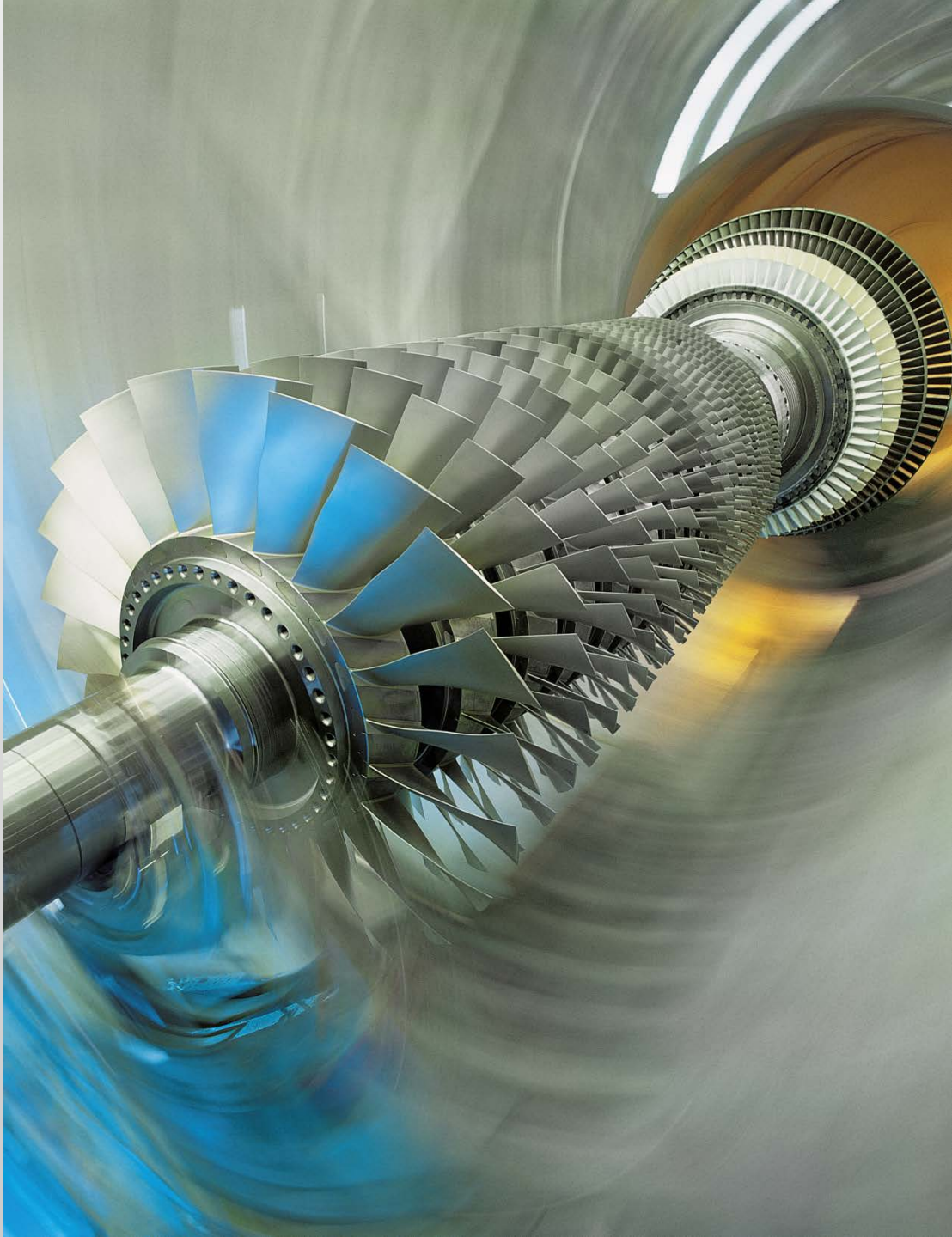
Kristin Gerdes, Walter Shelton – NETL

Charles White – Noblis

Arun Iyengar – Booz Allen Hamilton



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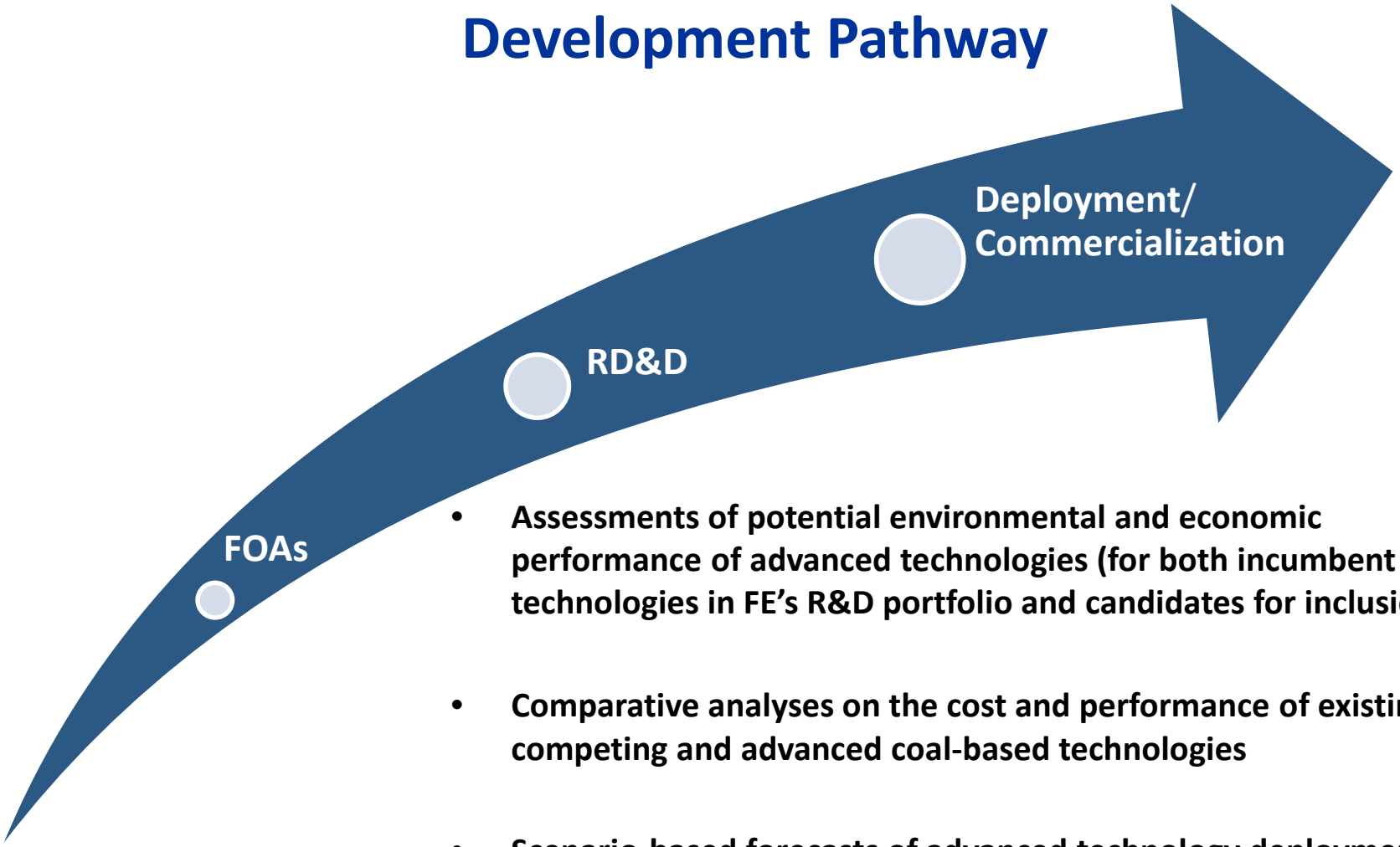
NETL's Office of Program and Performance in the Strategic Center for Coal Supports Full Technology Development Pathway



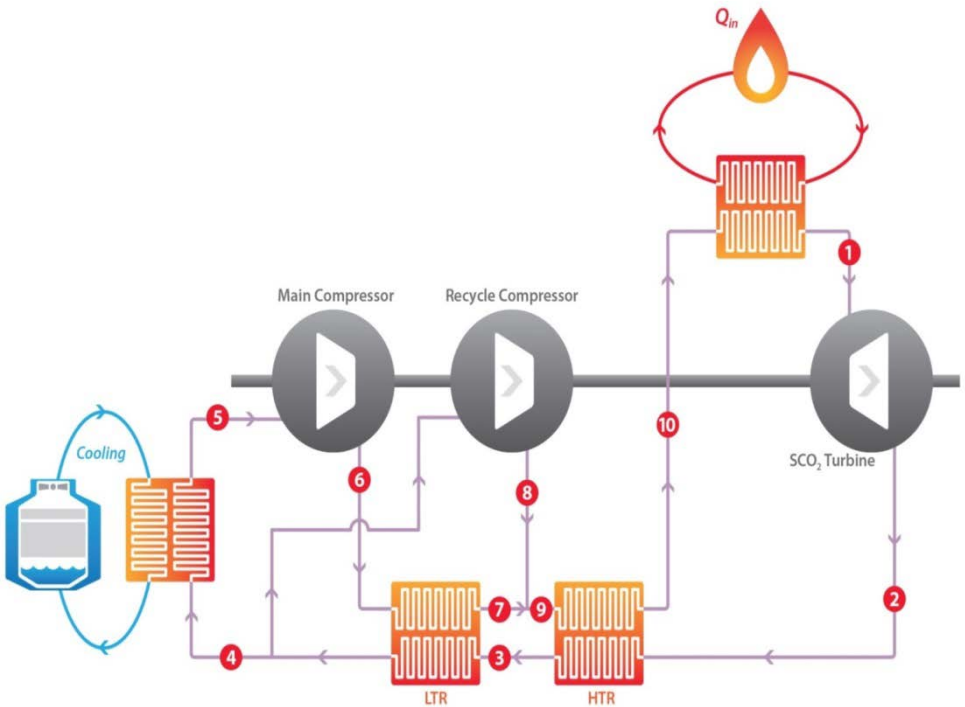
- **Assessments of potential environmental and economic performance of advanced technologies (for both incumbent technologies in FE's R&D portfolio and candidates for inclusion)**
- **Comparative analyses on the cost and performance of existing, competing and advanced coal-based technologies**
- **Scenario-based forecasts of advanced technology deployment and associated societal benefits (economic, environmental and security)**

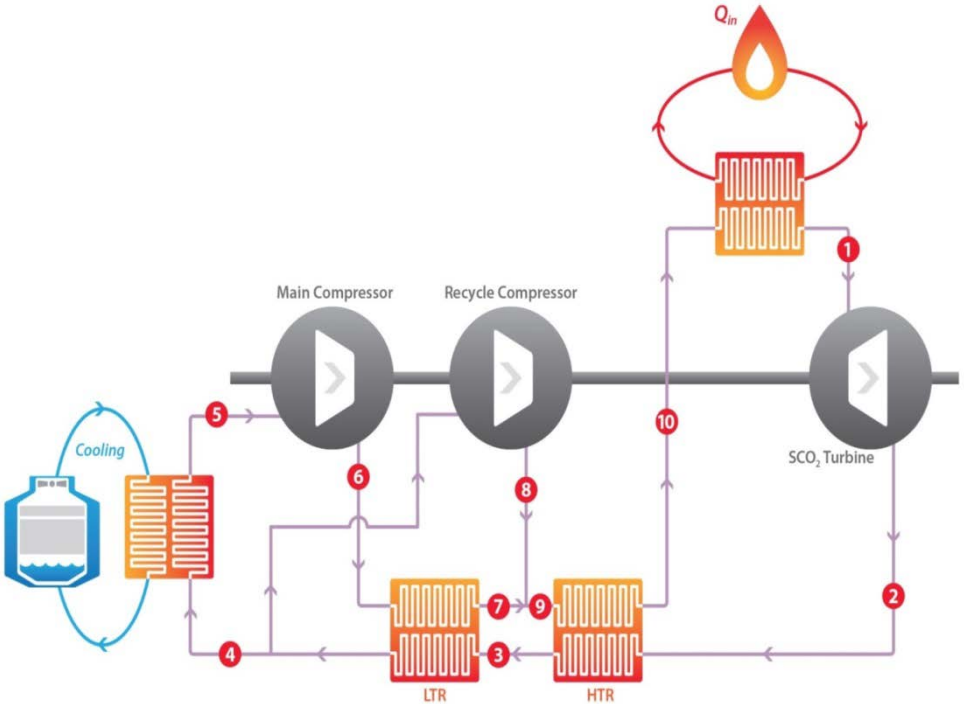
FOA = Funding Opportunity Announcement

Preliminary Benefits of SCO_2 Power Cycles

Outline

- **Potential plant-level benefits of SCO_2 cycles: Coal plant example**
- **Potential power sector benefits of SCO_2 cycles**





POTENTIAL PLANT-LEVEL BENEFITS FOR COAL-BASED INDIRECT SCO_2 CYCLES

Potential Benefits for Coal-Based Indirect SCO_2 Cycles: *Application and Efficiency*

- **Applicable to multiple coal-based platforms (air and oxygen-fired, PC, CFB, PFBC)**
  - Coal combustor modifications (and associated costs) needed to match temperature-enthalpy profile of SCO_2 cycles of interest

- **Substantial efficiency improvements anticipated as shown in table below**
  - Varies based on temperature, specific cycle configuration and heat integration

Power Cycle	Net Plant HHV Efficiency Improvement • in coal plants with 90% capture • relative to SC steam cycle[1]
AUSC Steam[2] 760°C (1400°F)	**+3.5%pts**
SCO_2 650°C (1200°F)	**+3 to 5%pts**
SCO_2 760°C (1400°F)	**+5 to 8%pts**

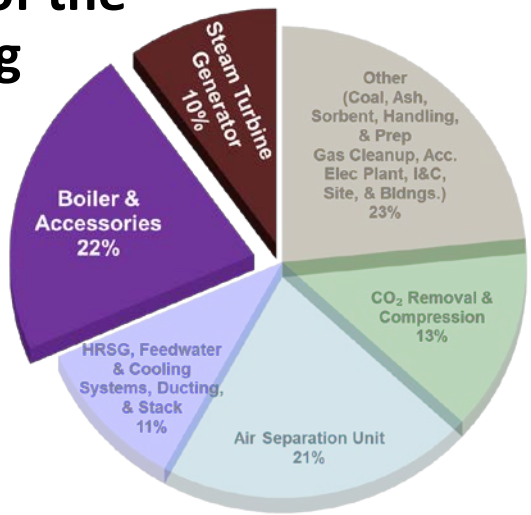
[1]SC = Supercritical 3500 psig/1100°F/1100°F
[2]AUSC = Advanced ultrasupercritical 5000 psig/1400°F/1400°F consistent with program targets

Coal-Based Supercritical CO_2 Cycles

Cost Uncertainties

- **Minimal information available on SCO_2 power island costs**
  - Turbomachinery expected to have lower costs due to lower pressure ratios and greater power density of SCO_2 relative to steam cycles
  - Configurations achieving high efficiency requires use of recuperators with large heat transfer areas
  - In general, achieving higher efficiencies requires additional cost
- **Modifications to base coal plant anticipated for most configurations which will likely increase cost of the combustor and associated heat transfer piping**
- **Cost sensitivity approach for this analysis*:**

	Adv. System Cost (Power Island + Coal Combustor) / Ref. System Cost (Power Island + Coal Combustor)
Low	100%
High	140%



**Assumes all cost changes in total plant cost come from power island and coal combustor cost, which represent 32 % of the total plant cost of the reference SC oxycombustion system*

Cost-Efficiency Trade-off for Adv. Power Cycles

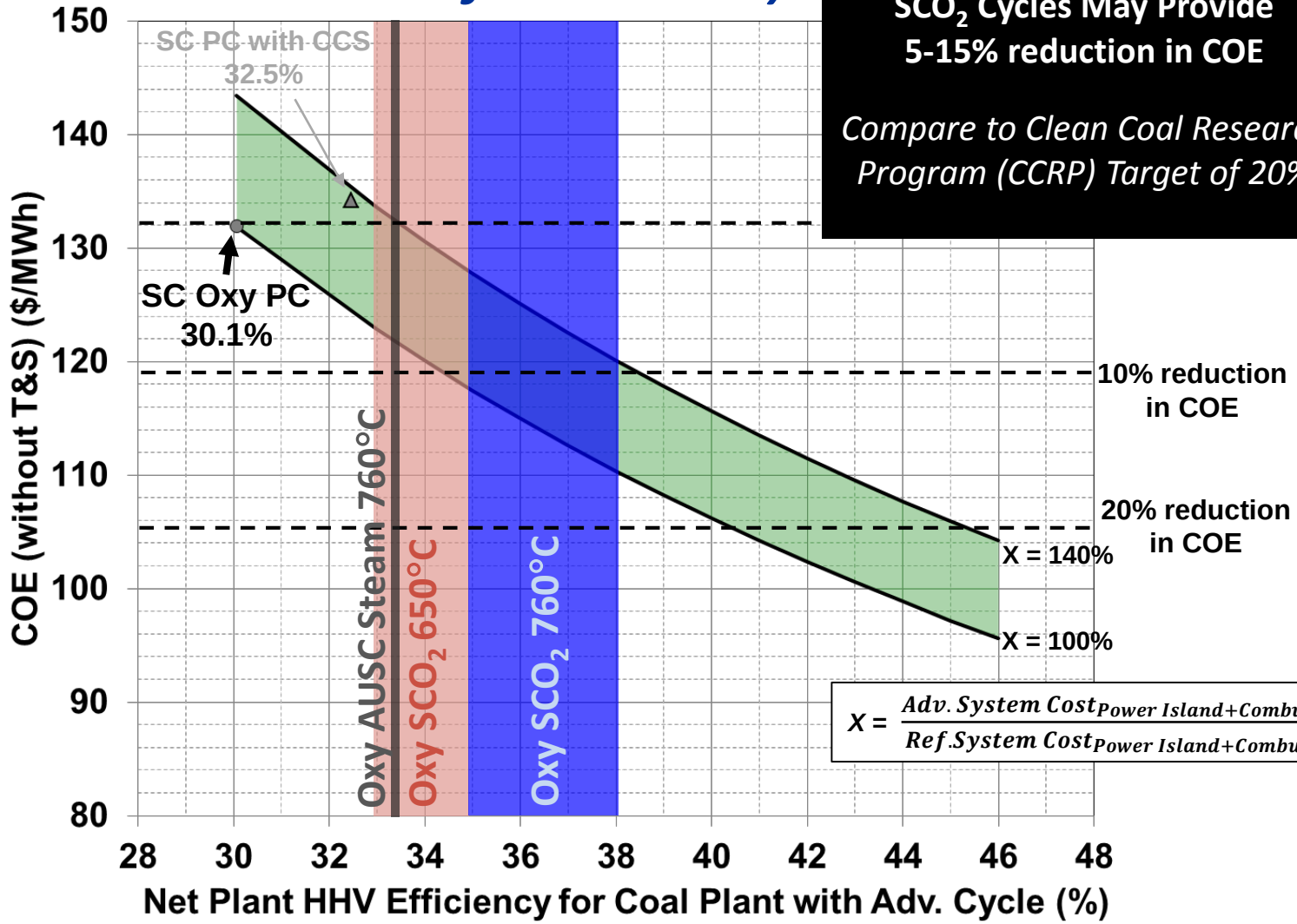
Cost of Electricity

SCO_2 Cycles May Provide 5-15% reduction in COE

Compare to Clean Coal Research Program (CCRP) Target of 20%

Reference: SOA SC Oxy-combustion

550 MW



$$X = \frac{Adv.\ System\ Cost_{Power\ Island+Combustor}}{Ref.System\ Cost_{Power\ Island+Combustor}}$$

Source: NETL

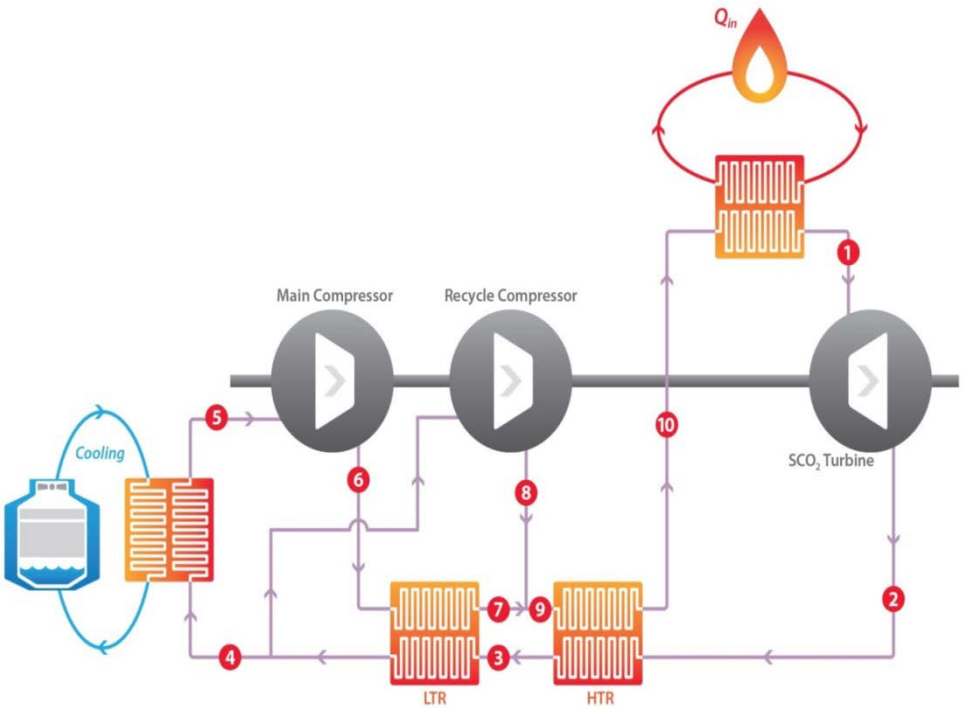
Potential Benefits for Coal-Based Indirect SCO_2 Cycles

- **Applicable to multiple coal-based platforms (air and oxygen-fired, PC, CFB, PFBC)**
- **Substantial efficiency improvements anticipated as shown in table below**
- **Significant cost uncertainties associated with SCO_2 power island (eg. recuperators) and combustor modifications**
- **Result: SCO_2 cycles may provide 5-15% reduction in COE**

Power Cycle	Net Plant HHV Efficiency Improvement	COE Change Attributable to Advanced Power Cycle	
	• in coal plants with 90% capture • relative to SC steam cycle[1]	Low Cost[3]	High Cost[3]
AUSC Steam[2] 760°C (1400°F)	+3.5%pts	-7 to -8%	+1 to -0%
SCO_2 650°C (1200°F)	+3 to 5%pts	-6 to -11%	+2 to -3%
SCO_2 760°C (1400°F)	+5 to 8%pts	-10 to -16%	-2 to -9%

[1]SC = Supercritical 3500 psig/1100°F/1100°F
[2]AUSC = Advanced ultrasupercritical 5000 psig/1400°F/1400°F consistent with program targets
[3]"Low Cost" assumes combustor + power island costs same as SC steam case;
"High Cost" assumes these sub-systems cost 40% more than for SC steam

No reduction
0 to 8%
> 8%



POTENTIAL POWER SECTOR BENEFITS FOR SCO_2 CYCLES

SCO_2 Power Cycle Preliminary Benefits Assessment: *Objective*

Identify potential national and international benefits associated with deployment of SCO_2 power cycle technology

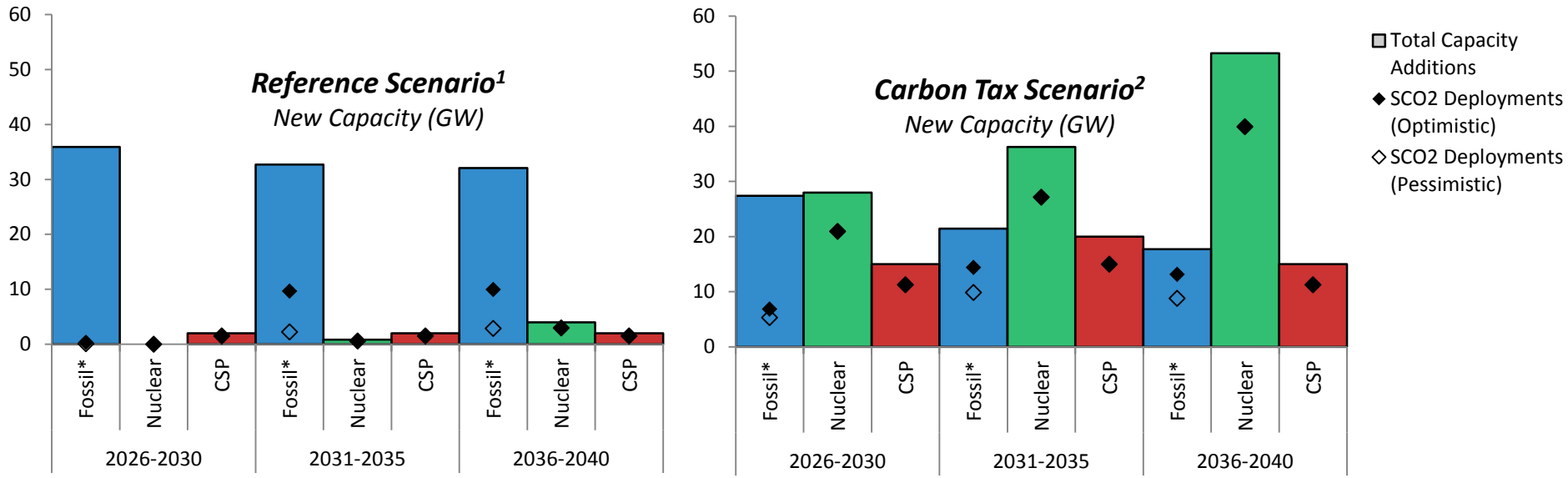
- **Consider reductions in the cost of power generation, CO_2 emissions and water consumption**
- **Consider fossil, nuclear and concentrating solar power (CSP) applications**

SCO_2 Power Cycle Preliminary Benefits Assessment: *Approach*

- **Examine new capacity forecasts for each base plant technology using 2 bounding scenarios**
- **Simplified approach to estimating the cost and performance benefits of plants with SCO_2 power cycles focuses on thermodynamic benefits with limited information on cost of the SCO_2 power cycle**
  - Ranges used to represent significant uncertainty in both performance and cost creating an "optimistic" and a "pessimistic" case
- **Plants with SCO_2 power cycles assumed to displace notional percentages of new capacity additions of steam-turbine-based conventional technologies with the same fuel type (assumed values ranging from 25% - 75%)**
  - Coal displacement of NGCC is a lower notional percentage due to geographically-limited CO_2 sales (~$40/tonne) for use in EOR; coal based sCO_2 must compete with NGCC so deployment levels are also dependent on technology optimism and natural gas prices.

SCO_2 Power Cycle Preliminary Benefits Assessment: *Deployments*

Potential deployments heavily influenced by the price of natural gas and carbon incentives



*All baseline fossil deployments are NGCC and NGCC with CCS; SCO_2 technology allows for coal with CCS to displace some NGCC deployments

[1]AEO 2014 Reference Case except for CSP which is derived from IEA's ETF 2DS Scenario (CSP as depicted in AEO 2014 does not allow for CSP + storage requiring the use of alternate projections)

[2]AEO 2014 GHG25 Case ($25/tonne CO2 tax beginning in 2015, escalating by 5% per year, real) except for CSP which is derived from EERE's SunShot Vision Study

SCO_2 Power Cycle Preliminary Benefits Assessment:
Accrued Benefits Through 2040

U.S. Benefits	**Reference Case**	**Carbon Tax Case**
Cost of Electricity Reduction for Fossil, Nuclear and CSP	~5-15%	
sCO_2 Capacity Deployed (GW)	13-28	150-160
Power Generation Cost Savings ($Billions)[1]	$0.6-$5	$8-$52
IRR Assuming $500M R&D Investment over 5 Years	10%-17%	29%-38%
Plant Level CO_2 Emissions Reduction (million tonnes)	0-172	80-89
International Benefits: Plant Level CO_2 Emissions Reduction (million tonnes)		14,700

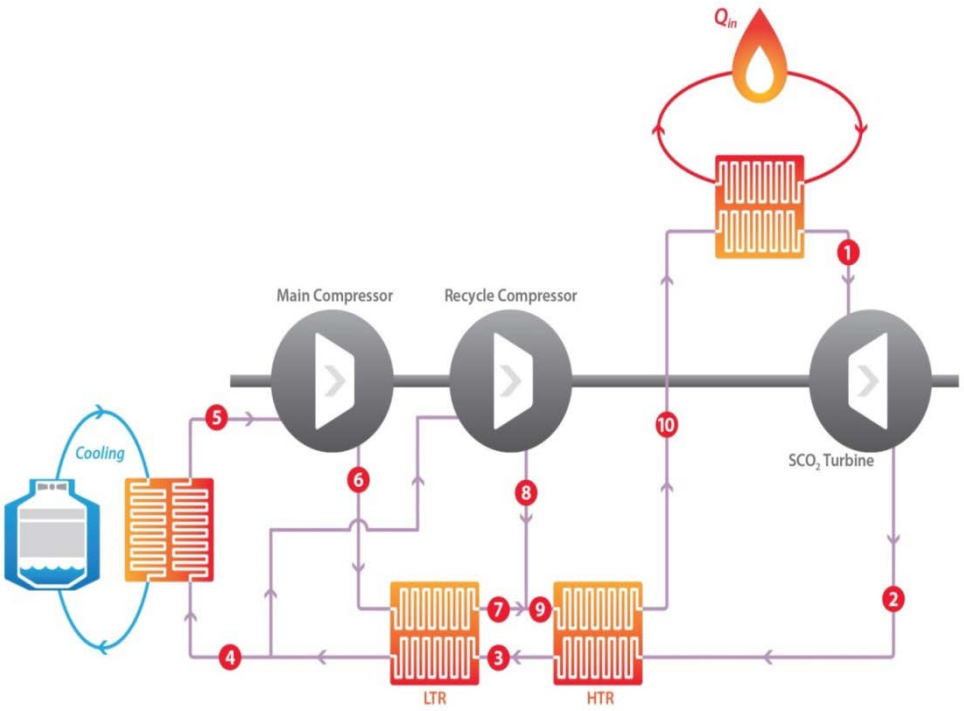
[1]2012 year dollars discounted at a 3 or 7% rate consistent with OMB A-94.

Results

- The ranges reflect uncertainties with technology performance, capital costs and natural gas price.
- U.S. GHG reductions are constrained by limited fossil displacement. Globally the CO_2 reduction is significant.
- Increased efficiency/reduced cost with sCO_2 enables coal with CCS (and EOR) to displace natural gas combined cycle w/o CCS.

SCO2 power cycles are ideally suited for dry cooling:

- Each GW of coal with sCO_2 with dry cooling displacing NGCC with wet cooling saves ~2 billion gals/year of water.
- If 4 of the 17 GW projected coal systems shifted to dry cooling, water consumption would be reduced by ~75 billion gallons through 2040 (9 billion gals/year in 2040).


Q_{in}
Main Compressor
Recycle Compressor
Cooling
SCO_2 Turbine
LTR
HTR
1
2
3
4
5
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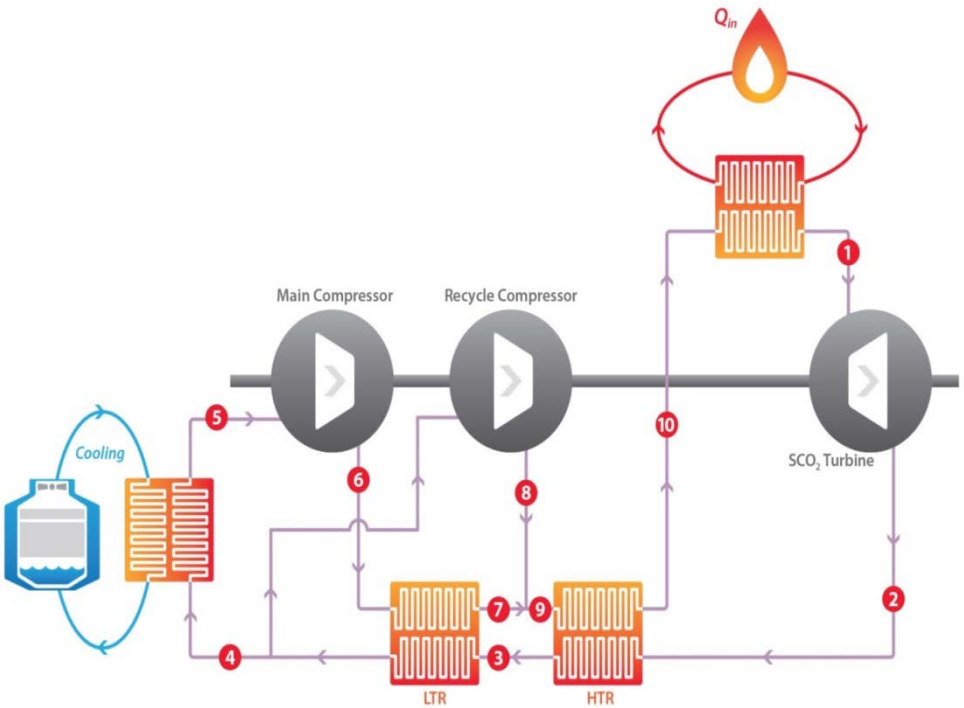
7
8
9
10

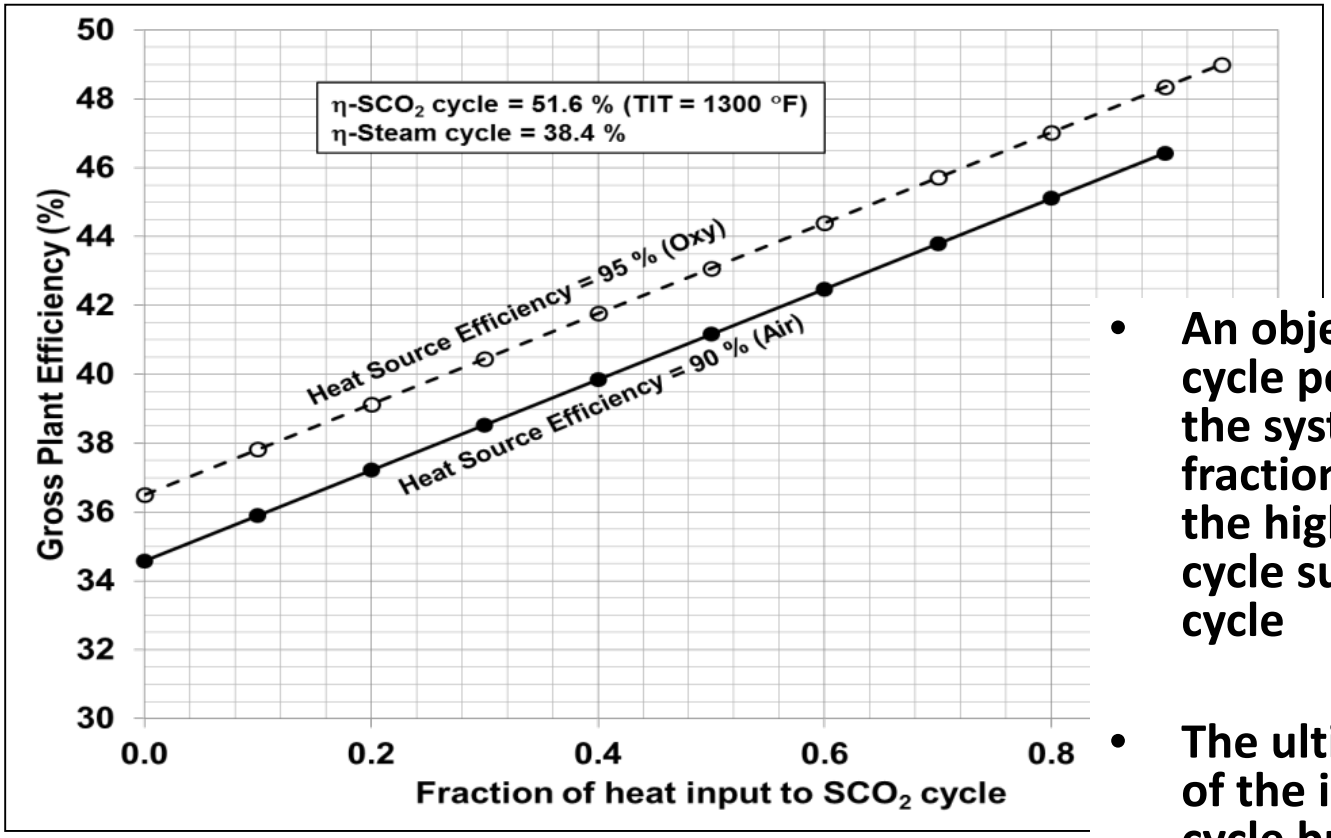
QUESTIONS?



BACK UP:
SCREENING OF FOSSIL-BASED HEAT SOURCES FOR INDIRECT SCO_2 CYCLES

Matching Heat Sources to Power Cycles

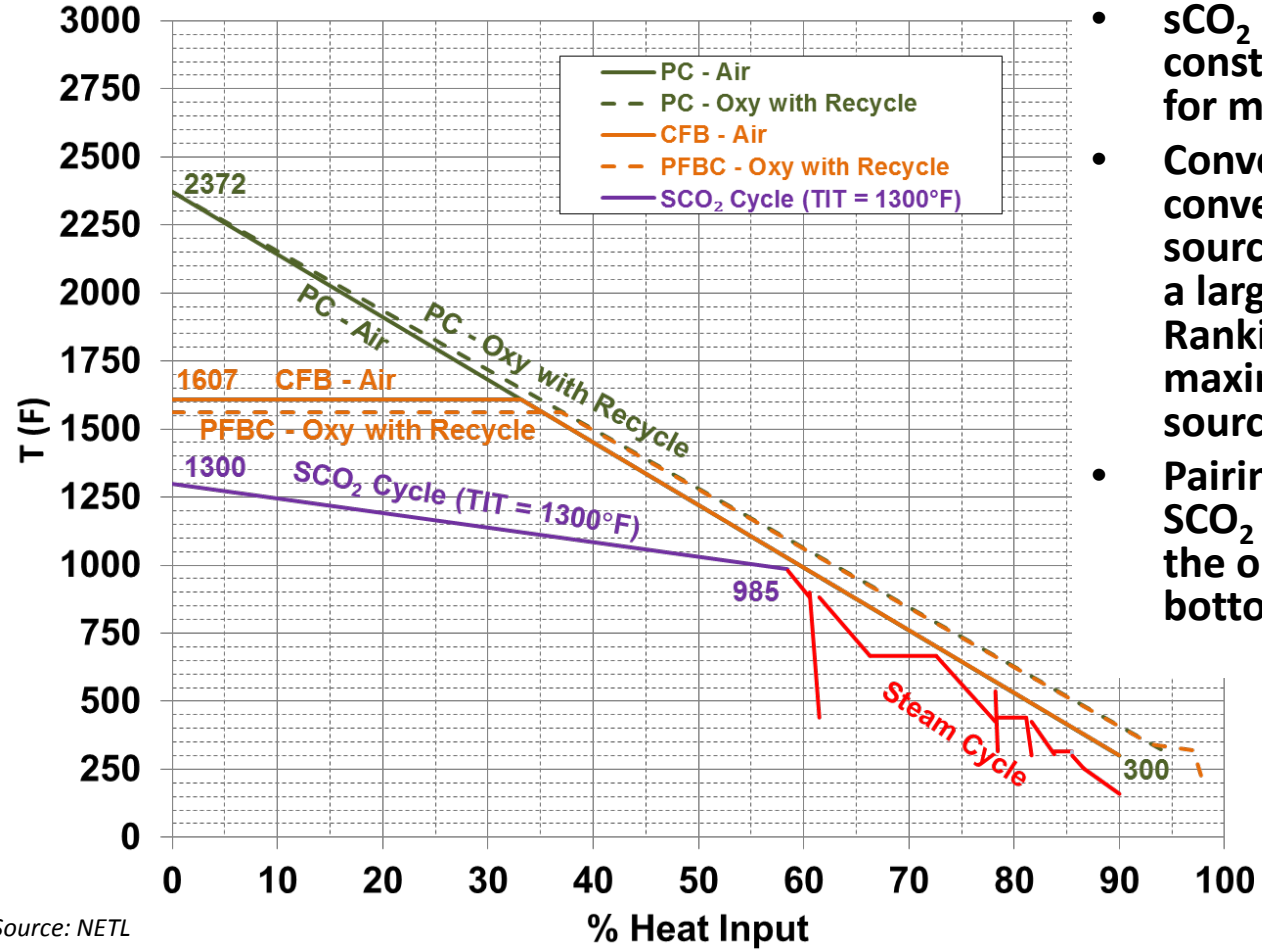
Minimizing Bottoming Cycles



- **An objective with combined cycle power plants is to design the system to maximize the fraction of input heat going to the higher efficiency topping cycle such as a sCO_2 Brayton cycle**
- **The ultimate goal is to use all of the input heat in the topping cycle but this is often difficult without wasting lower level heat**

Matching Heat Sources to Power Cycles

T-Q Diagram for Conventional Coal-Based Systems and example indirect SCO_2 cycle

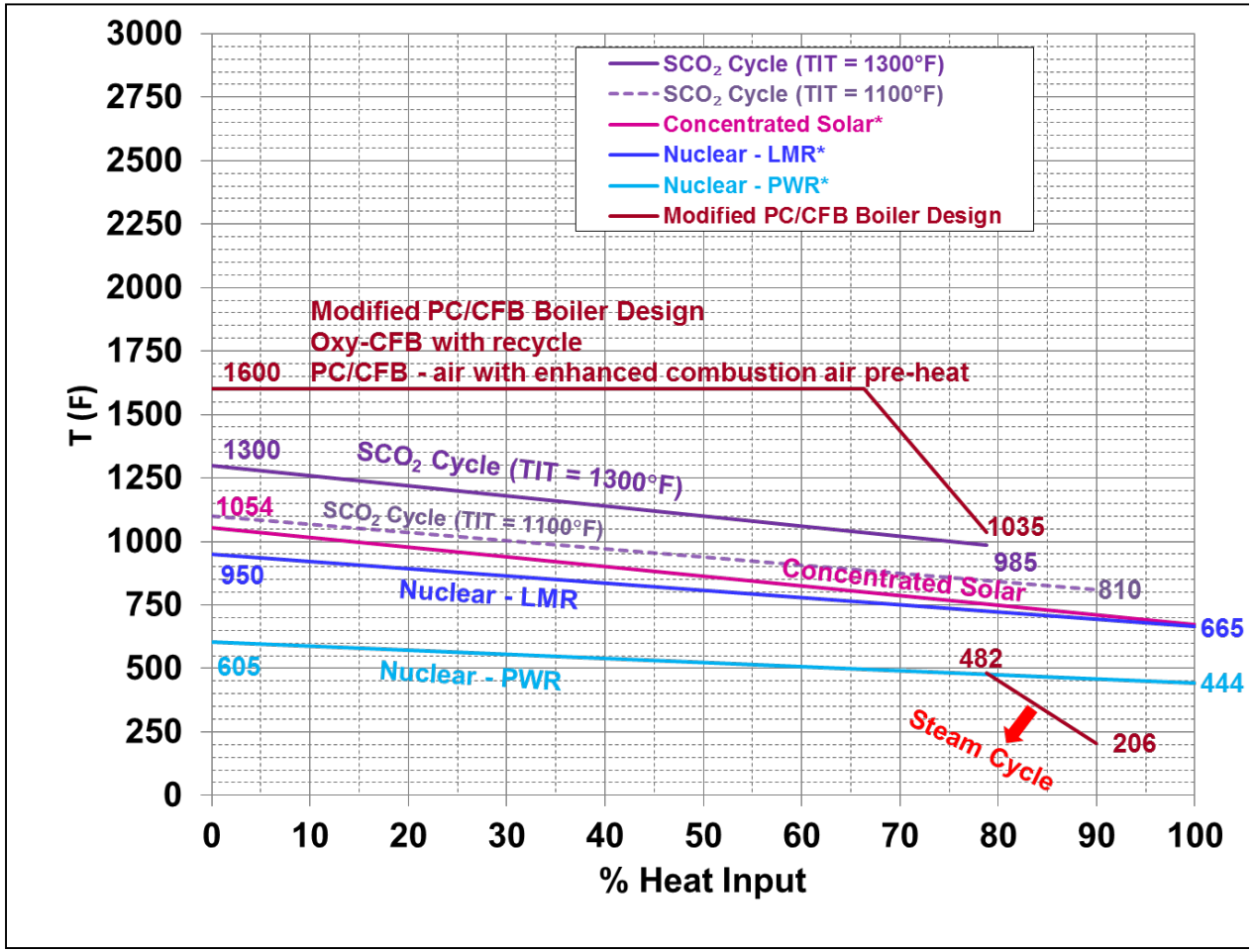


Source: NETL

- **sCO_2 cycle requires a relatively constant temperature heat source for maximum plant efficiency.**
- **Conventional PC, CFB, and conventional oxy-combustion heat sources provide a heat source with a large slope of T versus Q. Steam Rankine cycles have been tuned to maximize the use of this heat source temperature profile.**
- **Pairing theses heat sources and SCO_2 power cycle does not meet the objective of minimizing the bottoming cycle.**

Matching Heat Sources and Power Cycles

T-Q Profiles of Modified Coal-Based Systems



- **Adding enhanced preheat for combustion air or CO_2 recycle enables conventional PC, CFB, and PFBC air and oxy heat sources to be tailored to match the T versus Q profile required for a sCO_2 cycle.**

- **Modifications allow multiple coal-based systems (air, oxy, CFB, etc) to serve as a heat source for indirect SCO_2 power cycles while meeting the objective of minimizing the bottoming cycle.**