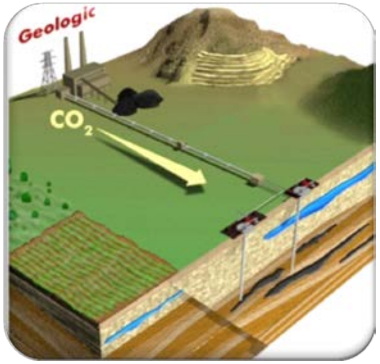


Power Cycles Based On Supercritical CO_2 – Applications, Challenges and Benefits to FE Power Systems

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U.S. DEPARTMENT OF ENERGY | Fossil Energy

Presentation Outline

Power Cycles Based On Supercritical CO_2 (SCO2) – Applications, Challenges and Benefits to FE Power Systems

- **Introduction**
  - Why SCO2 Power cycles
- **FE Applications**
- **Benefits**
- **Technical Challenges**
- **Summary / Conclusions**

Introduction

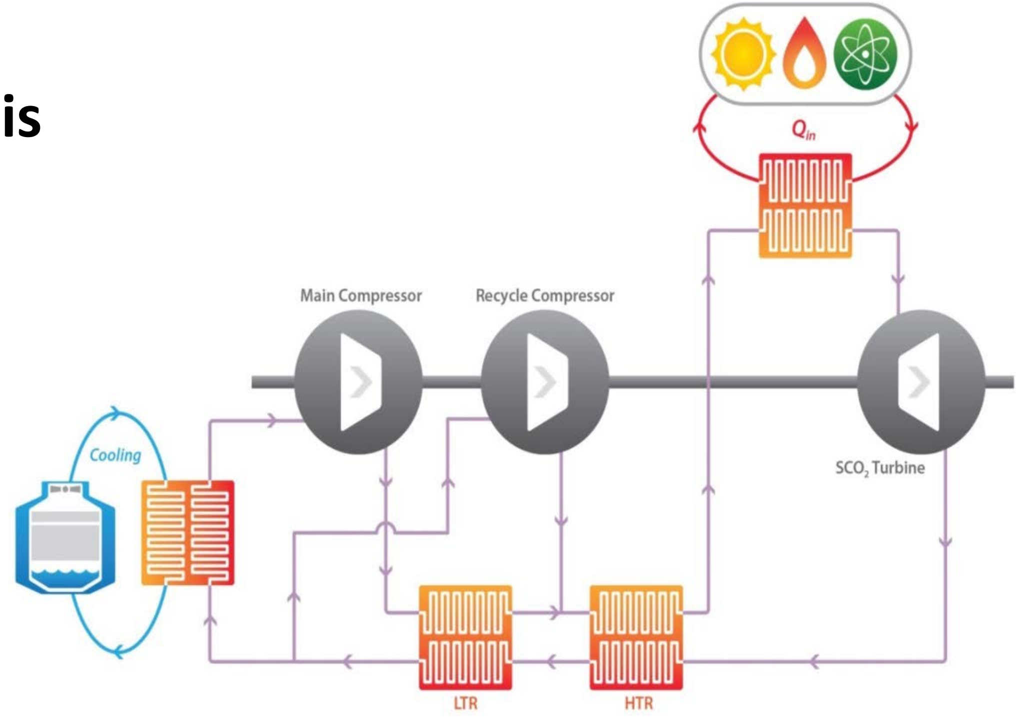
Why Supercritical CO_2 Power Cycles?

- **SCO2 power cycles have benefits across DOE power generation applications**
  - Fossil, nuclear, concentrated solar, geothermal, waste heat recovery, and ship board power
  - Accommodates a range of operating temperatures
- **SCO2 is an attractive working fluid**
  - CO_2 reaches a supercritical state at moderate conditions
  - Large fluid density (and low PR) keeps turbomachinery small
  - Less corrosive than steam, stable, inert
  - Better than other working fluids

Introduction

Why Supercritical CO_2 Power Cycles – Indirectly Heated Cycle?

- Thermal eff. > 50% possible
- ~ 50% of the cycle energy is recuperated heat
- low pressure ratio yields small turbo machinery
- Non condensing
- Ideally suited to constant temp heat source
- Adaptable for dry cooling



Recuperated Recompression Brayton (RCB) Cycle

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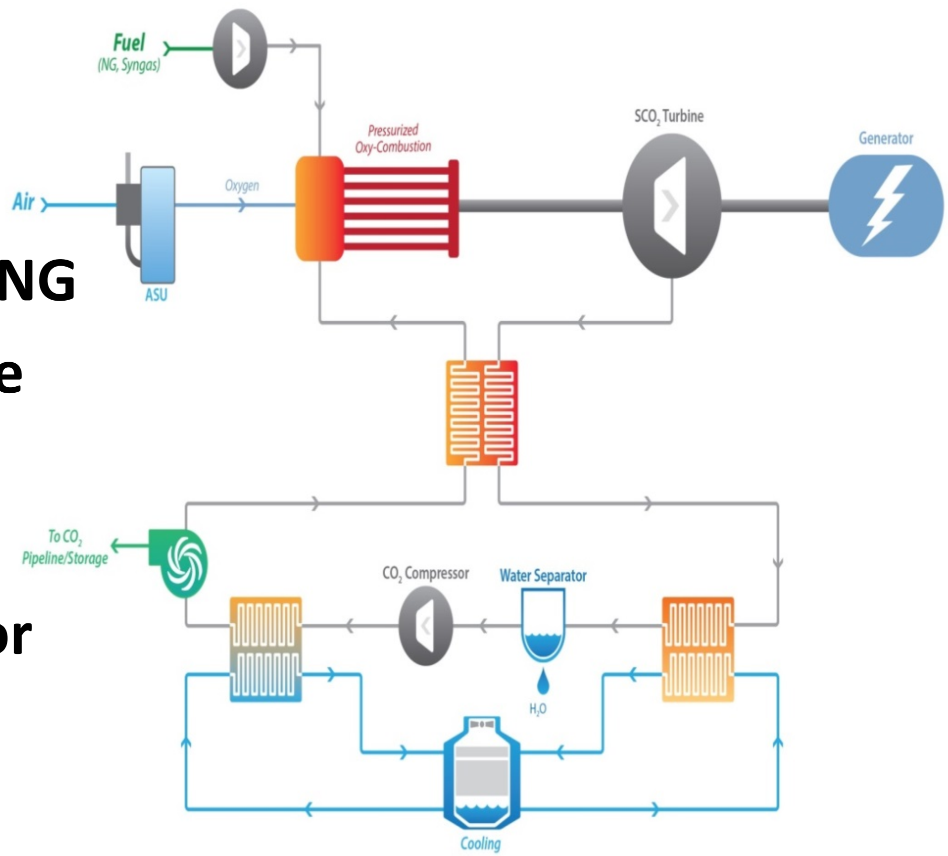
Introduction

Why Supercritical CO_2 Power Cycles – Directly Heated Oxy-fuel Cycle ?

- **Directly heated cycle compatible w/ technology from indirectly heated cycle**
- **Fuel flexible: coal syngas or NG**
- **100 % CO_2 capture at storage pressure**
- **Water producer**
- **Incumbent to beat: Adv. F- or H-class NGCC w/ post CCS**
    - **Nominally requires SCO2 TIT ~ 2,300 F or greater**



Directly Heated Oxy-fuel SCO2 Power Cycle

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FE Applications of SCO2 Power Cycles

Supports Coal Based Systems with Better Efficiency and Lower COE

- **SCO2 power cycles support two pathways within the FE portfolio of technologies (combustion and IGCC)**
- **Indirectly heated recuperated recompression brayton cycle**
  - Applicable to coal “boilers”
  - Replaces steam cycles
- **Directly heated oxy-fuel recuperated brayton cycle**
  - Applicable to coal based IGCC and natural gas
  - Replaces the conventional fossil fueled Brayton & Rankin Cycle
- **Both pathways have <u>similar</u> technology development requirements**

Benefit in Coal Based Applications

Efficiency and lower COE

- **Significant efficiency benefits depending on turbine inlet temperature**

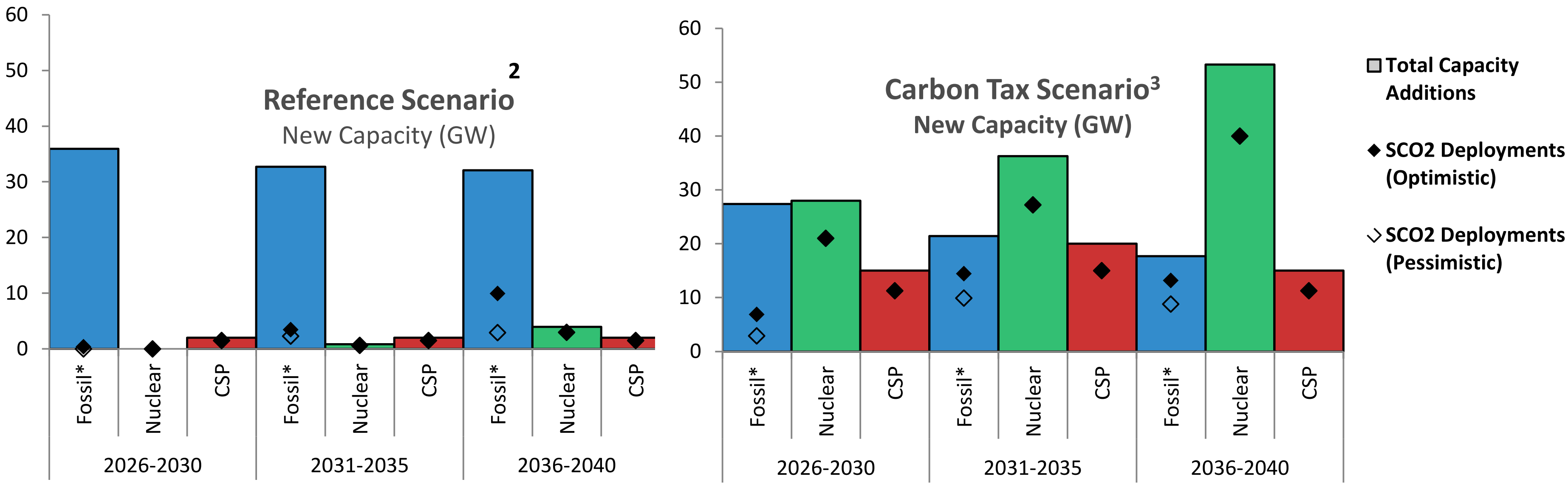
Power Cycle (indirect)	Net Plant Improvement [1]
AUSC Steam (1,400 F) [2]	3.5 % pts.
SCO2 (1,200 F)	3 - 5 % pts.
SCO2 (1,400F)	5 – 8 % pts.

[1]HHV, Relative to coal plant with supercritical steam conditions (3500 psig/1100°F/1100°F) and 90 % CO_2 capture
[2]AUSC = Advanced ultrasupercritical 5000 psig/1400°F/1400°F consistent with program targets

- **Capital cost benefit is currently less certain**
- **Efficiency benefit and capital cost assumptions reduce COE up to ~ 15 %**

Preliminary Benefits Assessment for three Applications: FE, CSP and Nuclear

- New capacity forecasts using 2 scenarios over 3 time period
- Assumed capacity replacement w/ SCO2 from 25%[1] -75%
- Deployments influenced by NG price 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

Accrued Benefits of SCO2 Technology
(2026 – 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
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 SCO2 enables coal with CCS to displace natural gas combined cycle w/o CCS

SCO2 power cycles are adaptable to dry cooling:

- 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)

Technical Challenges

Yes There are Many but the Benefits are Worth the Investment

- **Demonstrate turbo machinery performance**
  - Expander efficiencies > 90 % , compressor efficiencies ~ 85 %
- **Recuperator design, performance and cost**
- **High temperature materials**
- **Sub components: valves and seals**
- **Steady state and dynamic operation**
- **Overall system cost**
- **Challenges specific to FE applications**
  - Cycle configuration (indirect)
  - HT operation with SCO2 and 10 % water (direct)
  - Utilization of low grade heat (indirect and direct)
  - Furnace (boiler) heat transfer surface (indirect)

2014 FE Project Awards

Supercritical CO_2 Brayton Power Cycle R&D

- **Turbo Machinery for Indirect and Direct SCO2 Power Cycles**
  - Low-Leakage Shaft End Seals for Utility-Scale SCO2 Turbo (GE)
  - Adv. Turbomachinery Comp. for SCO2 Cycles (Aerojet Rocketdyne)
- **Oxy-fuel Combustors for SCO2 Power Cycles**
  - Coal Syngas Comb. for HP Oxy-Fuel SCO2 Cycle (8 Rivers Capital)
  - HT Combustor for Direct Fired Supercritical Oxy-Combustion (SwRI)
- **Recuperators / Heat Exchangers for SCO2 Power Cycles**
  - Low-Cost Recuperative HX for SCO2 Systems (Altex Tech. Corp)
  - Mfg. Process for Low-Cost HX Applications (Brayton Energy)
  - Microchannel HX for FE SCO2 cycles (Oregon State U)
  - HT HX for Systems with Large Pressure Differentials (Thar Energy)
  - Thin Film Primary Surface HX for Advanced Power Cycles (SwRI)
  - HX for SCO2 waste heat recovery (Echogen / PNNL, SBIR)
- **Materials**
  - Materials Issues for Supercritical carbon Dioxide (ORNL, FWP)

Summary / Conclusions

Power Cycles Based On Supercritical CO_2 (SCO2) – Applications, Challenges and Benefits to FE Power Systems

- **SCO2 power cycles have benefits across DOE power generation applications**
  - SCO2 is an attractive working fluid
- **Two FE pathways for SCO2 cycles identified**
  - Indirectly heated cycle (coal based PC boiler / furnace)
  - Directly heated cycle (coal based IGCC and NG)
- **Both pathways appear to have significant efficiency benefits that will reduce COE (~ 15% or higher)**
- **Need to validate capital cost reductions**
- **Resolve / address outstanding technical issues**
- **Significant project work established in 2014 to support SCO2 technology development & resolve technical issues**