NETL Activities in Supercritical CO2 Systems Analyses

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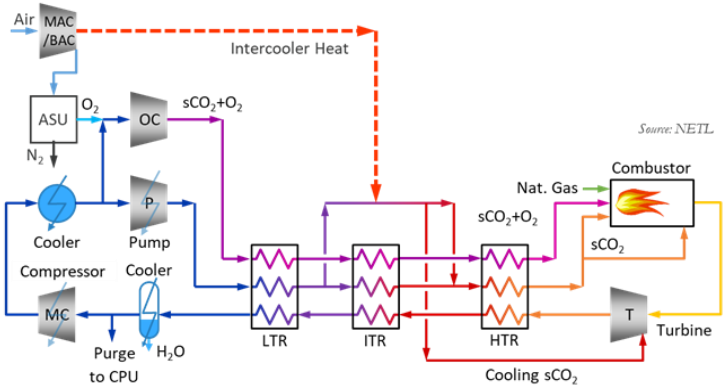
U.S. DEPARTMENT OF ENERGY

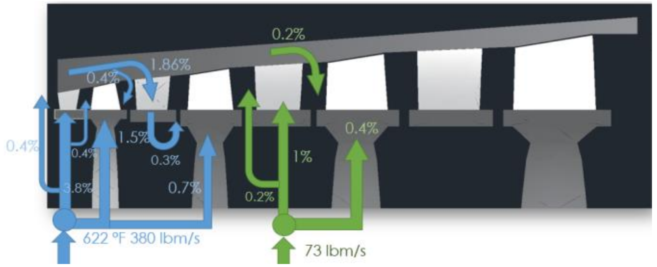
NATIONAL ENERGY TECHNOLOGY LABORATORY

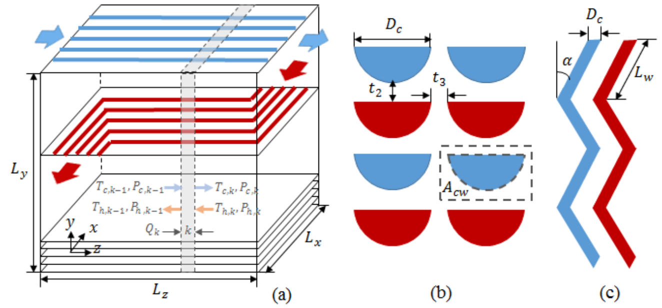
Techno-Economic Analysis - Direct Fired sCO_2

Net 650 MWe Exemplar Plant

- Optimized natural gas fired direct sCO_2 plant designs to minimize LCOE using NETL tool FOQUS (Framework for Optimization, Quantification of Uncertainty, and Surrogates)
- Uses cost models developed for sCO2 components*
- Uses custom models for turbine, PCHE, adiabatic air cooler
- Presented at 5th European sCO2 Symposium
  - Pidaparti S., White C. W., Liese E., and Weiland N., "Performance and Cost Potential for Direct-Fired Supercritical CO2 Natural Gas Plants", 5th European sCO2 Conf. for Energy Systems, March 14-16, 2023, Prague







Component	Scaling Parameter (Units)	Coefficients				Database Range (Range of Validity)	Uncertainty Range
		a	*b*	*c*	*d*		
Coal-fired heaters	Q (MW_{th})	820,800	0.7327	0	5.4e-5	187 to 1,450 MW_{th}	-23% to +26%
Coal-fired heaters	UA (MW_{th})	1,248	0.8071	0	5.3e-6	7.4e5 to 5.9e6 W/K	-16% to +21%
Natural gas-fired heaters	Q (MW_{th})	632,900	0.60	0	5.4e-5	10 to 50 MW_{th}	-25% to +33%
Recuperators	UA (W/K)	49.45	0.7544	0.02141	0	1.6e5 to 2.15e8 W/K	-31% to +38%
Direct air coolers	UA (W/K)	32.88	0.75	0	0	8.6e5 to 7.5e7 W/K	-25% to +28%
Radial turbines	$\dot{W}_{sh}$ (MW_{sh})	406,200	0.8	0	1.137e-5	8 to 35 MW_{sh}	-32% to +51%
Axial turbines	$\dot{W}_{sh}$ (MW_{sh})	182,600	0.5561	0	1.106e-4	10 to 750 MW_{sh}	-25% to +30%
IG centrifugal compressors	$\dot{W}_{sh}$ (MW_{sh})	1,230,000	0.3992	0	0	1.5 to 200 MW_{sh}	-40% to +48%
Barrel type compressors	$\dot{V}_{in}$ (m^3/s)	6,220,000	0.1114	0	0	0.1 to 2.4 m^3/s	-30% to +50%

*N. T. Weiland, B. W. Lance and S. R. Pidaparti, "sCO2 Power Cycle Component Cost Correlations From DOE Data Spanning Multiple Scales and Applications," in ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, 2019

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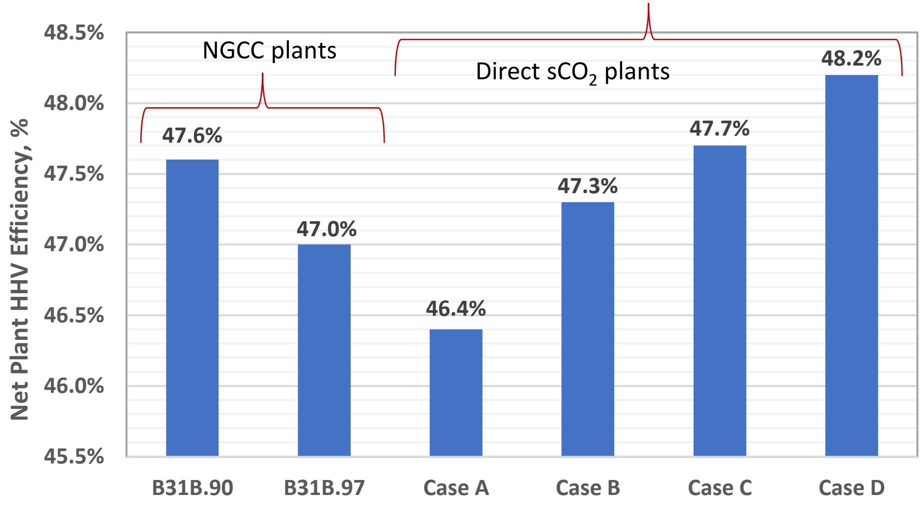
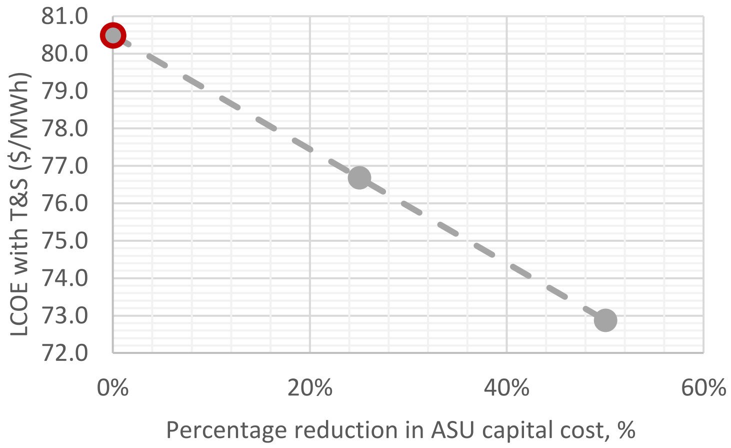
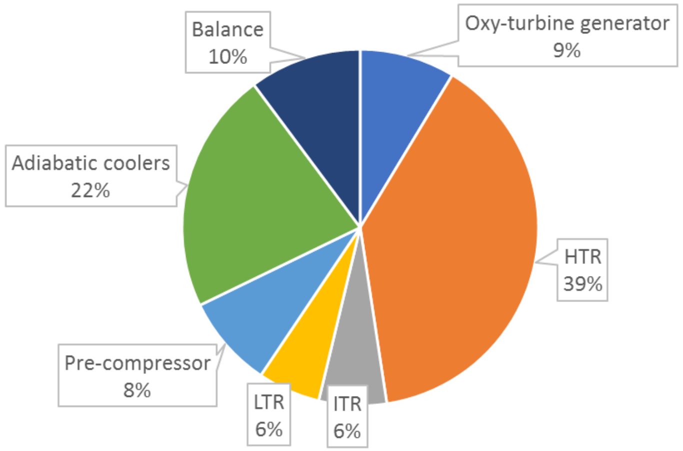
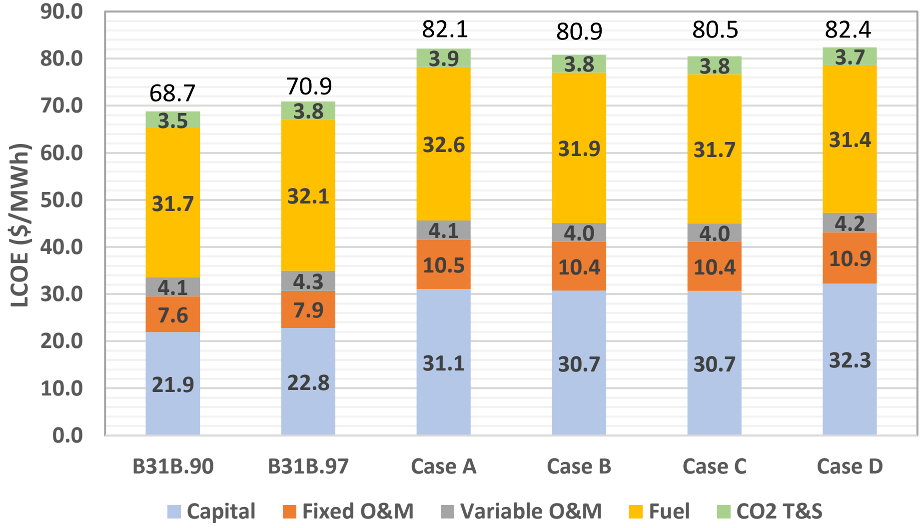
Net 650 MWe Exemplar Plant Results

- Direct sCO_2 plants achieve similar or higher plant efficiency compared to NGCC plants with CCS while offering higher CO_2 capture rates (~99%)
  - Heat integration between ASU and power cycle is crucial to achieve high plant efficiencies
- LCOE is higher than NGCC plants with CCS due to high capital costs associated with ASU, recuperators
- Assumed firing temperature of 1200°C. Plan future study to examine lower firing temperatures





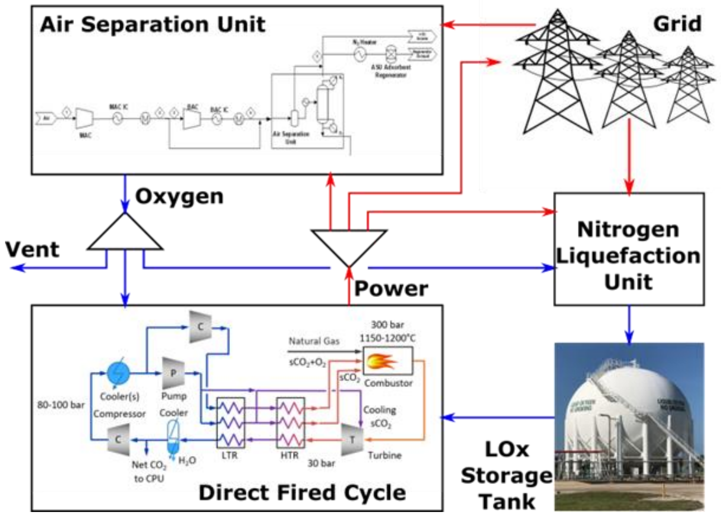


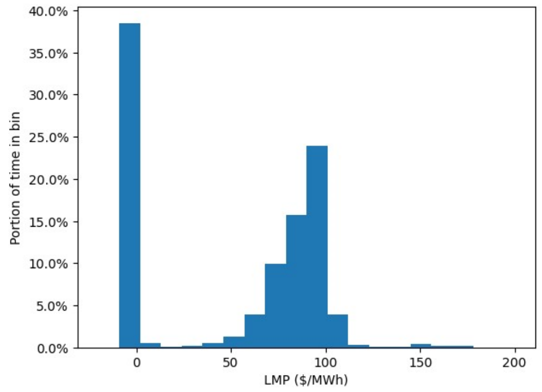


Techno-Economic Analysis - Direct Fired sCO_2

Potential Benefits of Liquid Oxygen Storage

- Liquid oxygen (LOX) storage allows independent operation of the ASU and power cycle, providing an opportunity to improve economics in a bi-modal, high variable renewable energy (VRE) energy pricing environment*
- Using NETL IDAES software to perform a multi-period optimization of net present value (NPV)
- Preliminary results indicated LOx storage could improve plant economics
  - However, Argon production from the ASU could dramatically impact results
- Expanding study to include effects like plant scale, cycling cost, argon sale, ASU cost, and alternative pricing signals (not bi-modal)





*Frequency plot of Predicted 2035 LMP price for CAISO at $100/tonne tax

*Cohen and Durvasulu (2021): NREL Price Series Developed for the ARPA-E FLECCS Program.

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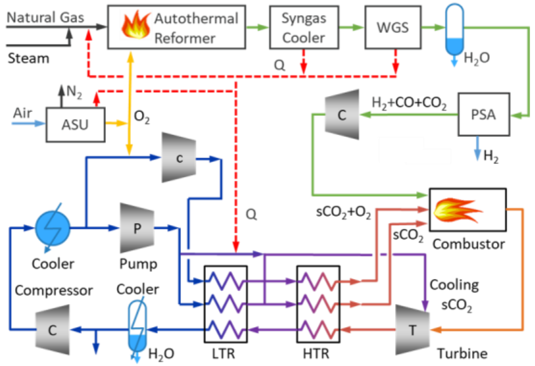
Hydrogen and Power Co-Production Using Direct sCO_2 Power Cycles

- Analyzed potential synergies between an ATR hydrogen production process and the direct sCO_2 plant
- Table to right shows results for LCOE and LCOH of integrated system compared to standalone systems
- For integrated system LCOE 9% lower than standalone direct fired cycle, but LCOH 3% higher than standalone ATR
  - Estimate 4-5% benefit in "overall" levelized cost
  - However, an integrated system will bring practical operational challenges
- Could not complete all scenarios, for instance, including water gas shift (WGS) for increased hydrogen production (but less electricity)
- System scaling optimization was not in scope, but could impact analysis



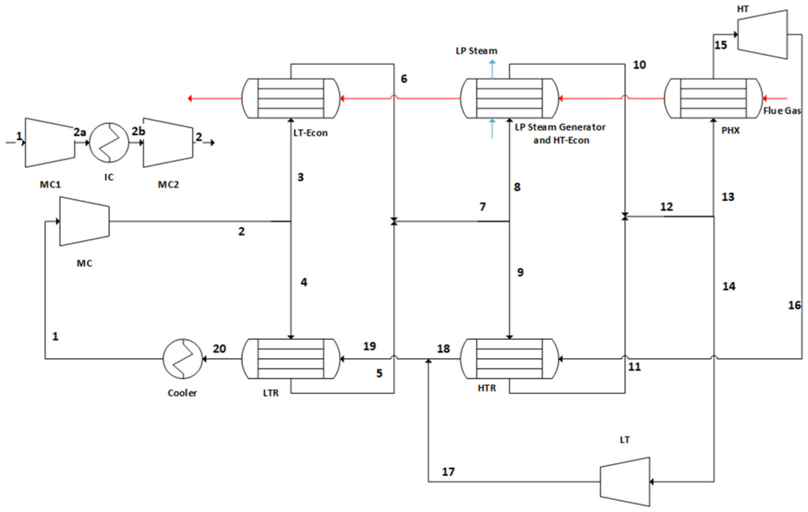
Component Breakdown	Allam Cycle (Case C) CF = 85% LCOE ($/MWh)	ATR Plant (Case 3) †CF = 85% ††LCOH ($/kg)	Co-Production without WGS Exemplar Values at CF = 85%	
			LCOE ($/MWh)	LCOH ($/kg)
Capital	30.7	0.34	43.4	1.29
Fixed (O&M)	10.4	0.12	15.1	0.45
Variable O&M	4.0	0.36	6.0	0.18
Fuel	31.7	0.77	58.2	1.73
Hydrogen Product Sale	0.0	N/A	-56.5	N/A
Electricity Product Sale	N/A	0.00	N/A	-2.13
Total (Excluding T&S)	76.7	1.59	66.2	1.52
CO_2 T&S	3.8	0.09	7.2	0.21
Total (Including T&S)	**80.5**	**1.68**	**73.4**	**1.73**

†ATR financial factors in NETL Baseline report were adjusted to match sCO2 factors. CF changed from 90% to 85%; FCR from 0.0586 to 0.0707; TASC/TOC from 1.070 to 1.093.
††Electricity = $71.7/MWh when calculating LCOH for ATR

Indirect sCO_2 Systems

Bottoming Cycle for Gas Turbine with Carbon Capture

- NETL optimization tools used to develop LCOE-minimized indirect sCO_2 bottoming cycle designs for an "H-Class" turbine
- Compared to NETL baseline study for NGCC with steam bottoming cycle and 95% carbon capture (B32B.95)
- Results showed potential for similar LCOE to steam bottoming cycle, improving with higher assumed exhaust gas temperature (EGT)
- Currently looking at off-design performance



"Modified Brayton" cycle has no HTR or bypass turbine (zero flow to streams 8 and 14)

	B32B.95 EGT = 596.0°C	Modified Brayton (LT-Econ) EGT = 596.0°C	Modified Brayton (LT-Econ) EGT = 629°C
LCOE ($/MWh)			
Capital	20.6	20.3	20.0
Fixed O&M	7.0	6.9	6.8
Variable O&M	3.9	3.8	3.8
Fuel	31.0	31.1	31.2
Total (Excluding T&S)	*62.4*	*62.1*	*61.7*
CO_2 T&S	3.6	3.6	3.5
Total (Including T&S)	*66.0*	*65.7*	*65.2*

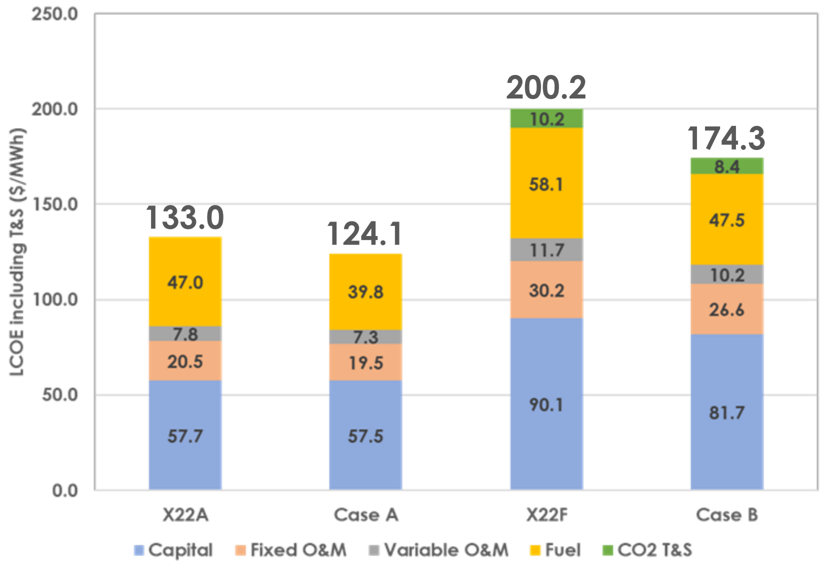
Indirect sCO_2 Systems

Biomass sCO2 Cycle Study

- NETL optimization tools used to develop LCOE-minimized indirect sCO_2 plant designs using a 100% biomass fired circulating fluidized bed (CFB) heat source (leverages previous coal-fired analyses)
- The plants were designed to achieve net-zero or net-negative CO_2 emissions. Collaborating with the life cycle analysis team to calculate the CO_2 emissions over the plant lifetime
- Results indicate lower LCOE with sCO_2 cycle
  - Planned journal paper will include 35% and 50% biomass moisture results

Case	Fuel	Unit Cycle	Power Generation	Oxidant
Case X22A	Hybrid Poplar (80%)/ Forest Residue (20%)	Air Fired-CFB	Supercritical steam cycle (3500psig/1100°F/1100°F)	Air
Case A			sCO_2 power cycle (RCBC with turbine reheat)	
Case X22F		Oxy-CFB	Supercritical steam cycle (3500psig/1100°F/1100°F)	95% Oxygen
Case B			sCO_2 power cycle (RCBC with turbine reheat)	

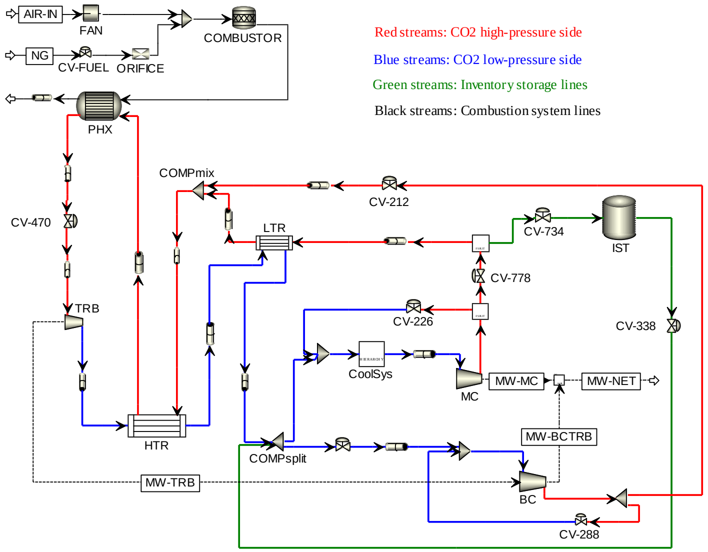
Preliminary results for 20% moisture biomass

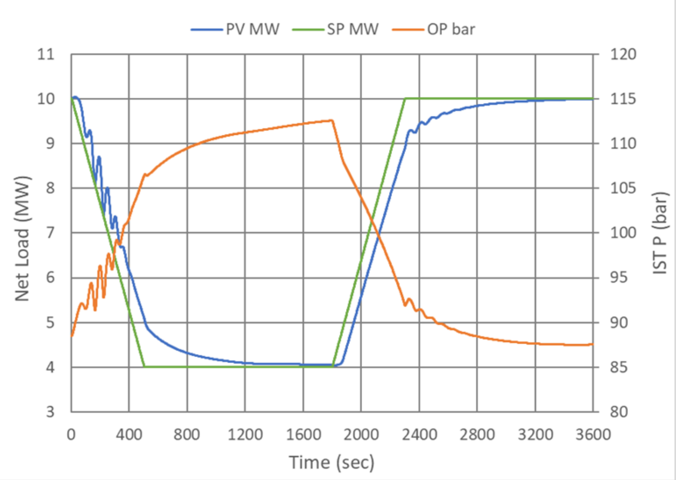


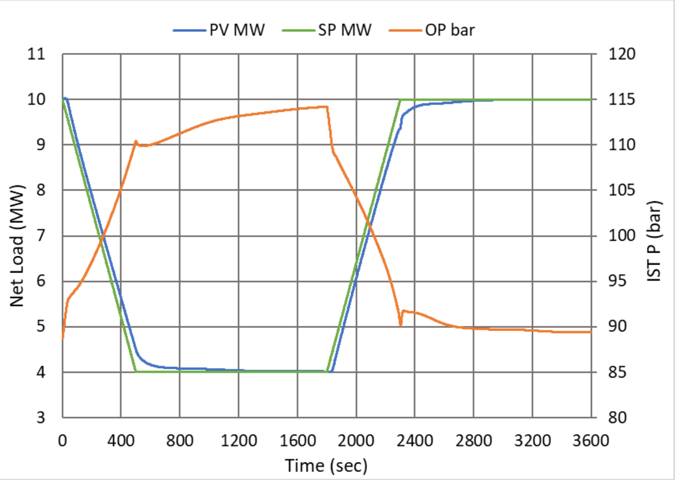
Indirect sCO_2 Systems

10 MWe Recompression Brayton Cycle Modeling and Control

- Conducted load following studies for 10 MW recompression closed Brayton Cycle
  - Looked at multiple approaches to reducing cycle oscillations, allowing for closer load following
  - Bottom right figure shows improved setpoint load following achieved with better main cooler CO2 outlet temperature control
- Uses Aspen Dynamics incl. custom models built over previous years





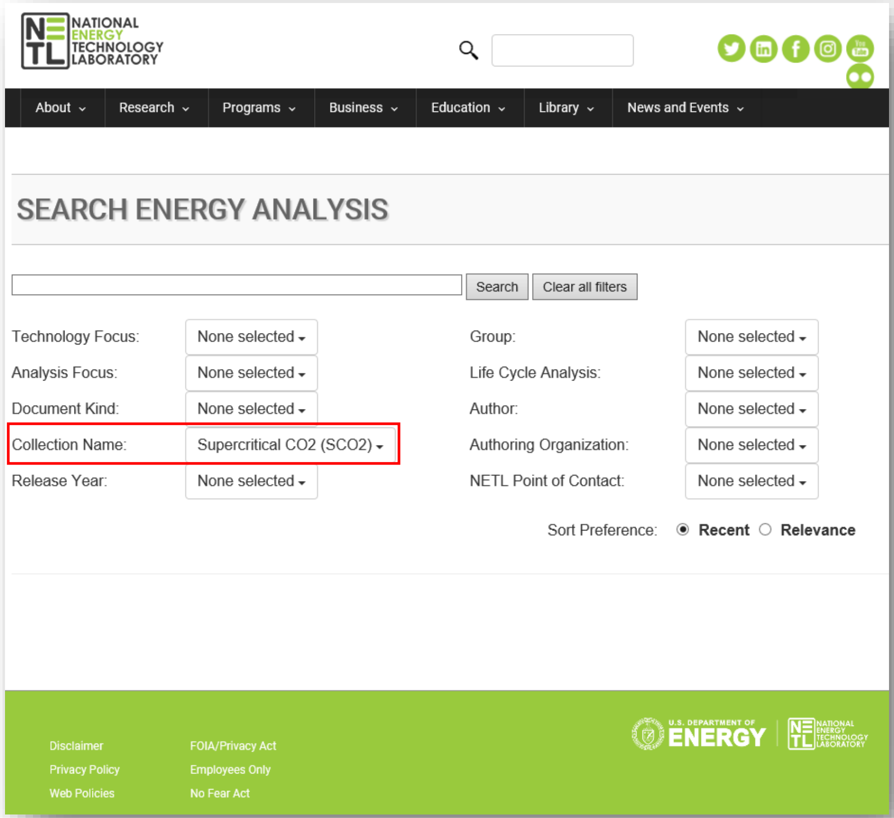


Results showing load setpoint (SP MW), actual load (PV SP) and inventory storage tank pressure (IST P) for a 7.5%/min load ramp before (top) and after (bottom) control additions

NETL's sCO_2 Techno-Economic Analyses

Finding our Research

- On www.OSTI.gov:
  - Search for: Subject = sCO2 AND Research Org = NETL
- On www.netl.doe.gov:
  - Go to:
    Research and Programs >
    Energy Analysis >
    Search Energy Analysis
  - Link to Website
  - Search: Collection Name = Supercritical CO2 (SCO2)



SEA's sCO_2 Analyses

- **Preliminary commercial-scale sCO_2 techno-economic analyses:**
  - Oxy-coal CFB indirect sCO_2 plant with carbon capture & storage (CCS) – 2017
  - Air-fired coal CFB indirect sCO_2 plant *without* CCS – 2019
  - Coal gasification integrated with direct sCO_2 plant with CCS – 2018
  - Natural gas-fueled direct sCO_2 plant with CCS – 2019
- **Detailed focus area studies for sCO_2 plant cost and efficiency improvements:**
  - PCHE 1D design and dynamic model – Journal of Applied Energy, 2018
  - sCO_2 component cost scaling study – ASME Turbo Expo 2019 (GT2019-90493)
  - sCO_2 cooling system cost and performance models – March 2020
  - Indirect sCO_2 cooling system integration study – 3rd European sCO_2 Conference, 2019
  - Direct sCO_2 cooling system integration study – 7th sCO_2 Symposium, 2020/2021
  - Indirect sCO_2 heat source integration study – 7th sCO_2 Symposium, 2020/2021
  - Air separation unit modeling and integration (direct sCO_2)
  - Direct sCO_2 turbine modeling – Journal of Energy Conversion and Management, 2022

SEA's sCO_2 Analyses

- **Detailed studies for sCO_2 plants:**
  - Exemplar 650 MW indirect sCO2 coal plant optimization with and without CCS – ASME Turbo Expo, GT2021-58865, GT2021-58867
  - Direct sCO_2 techno-economic analysis optimization - 5th European sCO2 Conference for Energy Systems. March 14-16, 2023, Prague, Czech Republic
    - The same study with more detail
  - Techno-economic analysis of a NGCC plant with a sCO_2 bottoming cycle
    - Without CCS – NETL report, Nov. 2020
    - With CCS - Paper in progress for 8th Supercritical CO2 Power Cycles Symposium, Feb. 2024
  - Dynamic modeling of 10 MW recompression Brayton cycle
    - Load following, warm shutdown and startup – Journal Applied Energy, 2020
    - Oscillation mitigation during faster load following – Journal of Applied Energy, 2023
  - Papers in progress for biomass plant, hydrogen and power co-production, and liquid oxygen storage potential for the direct-fired cycle

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Questions/ Comments

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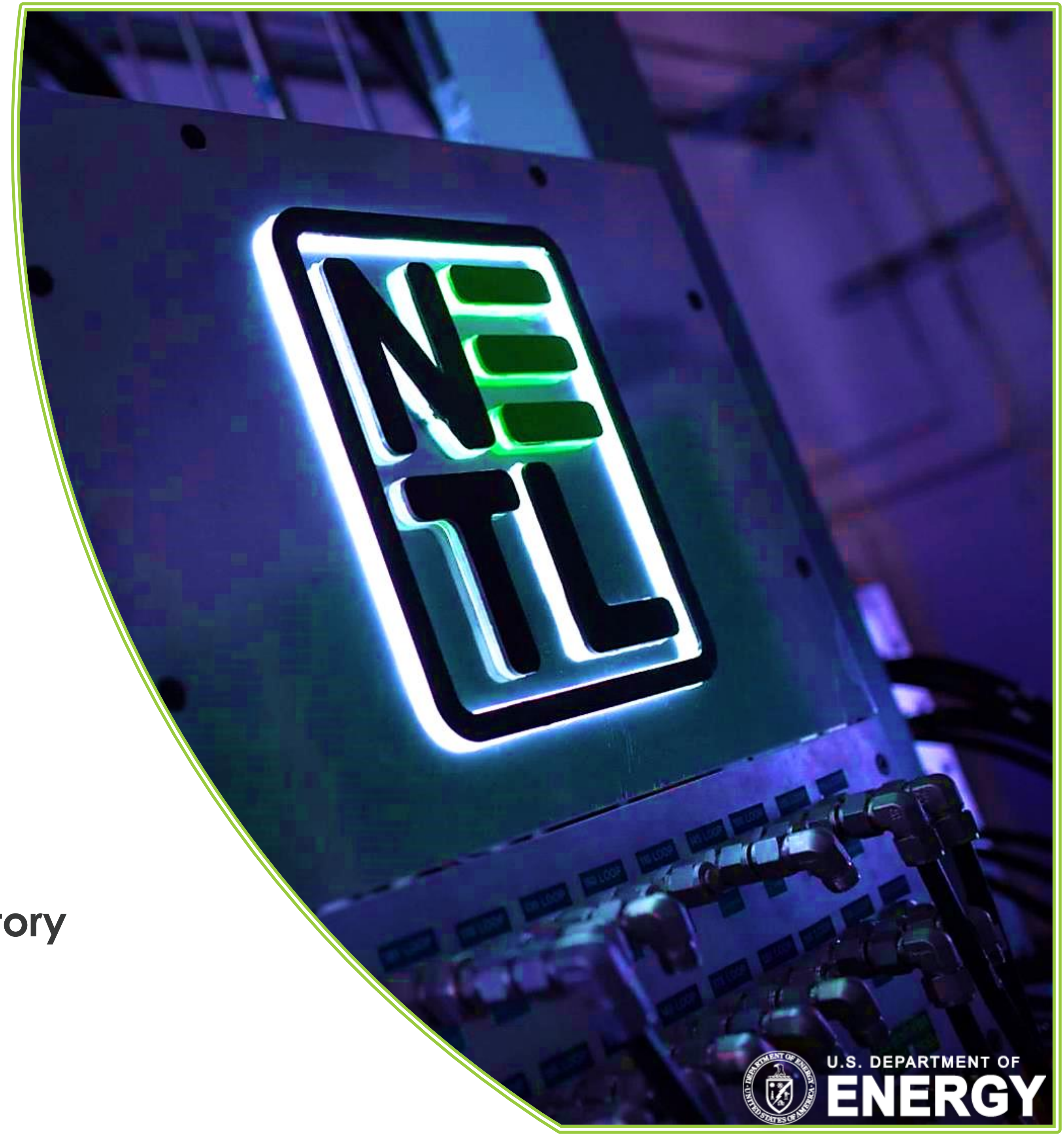

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