SAND2019-11668C

Progress Toward Commercial Deployment of sCO2 Brayton Power Cycles

October 1-4 2019, Daegu, South Korea

Matthew D. Carlson, Sandia National Laboratories

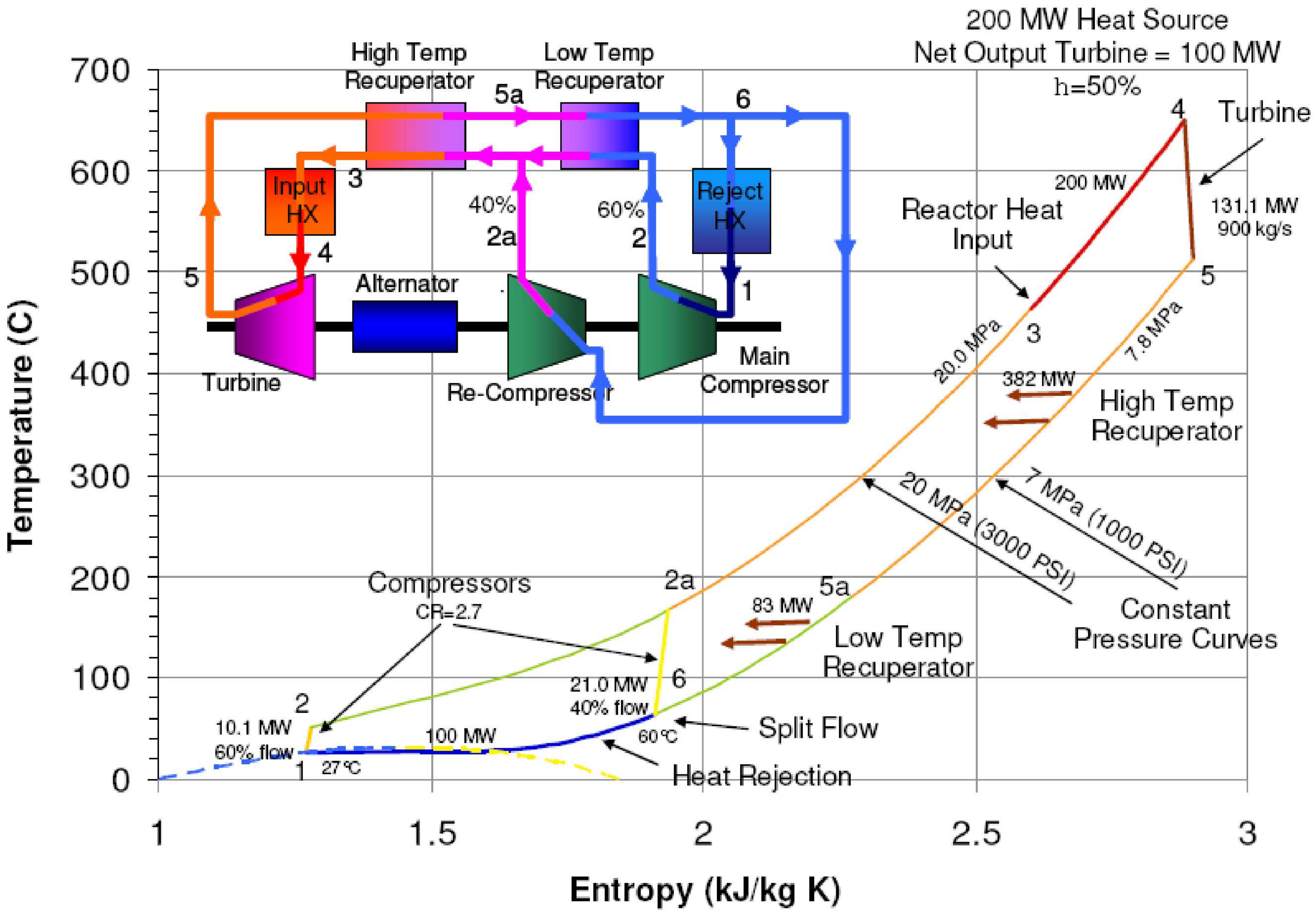
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2019-XXXXX C

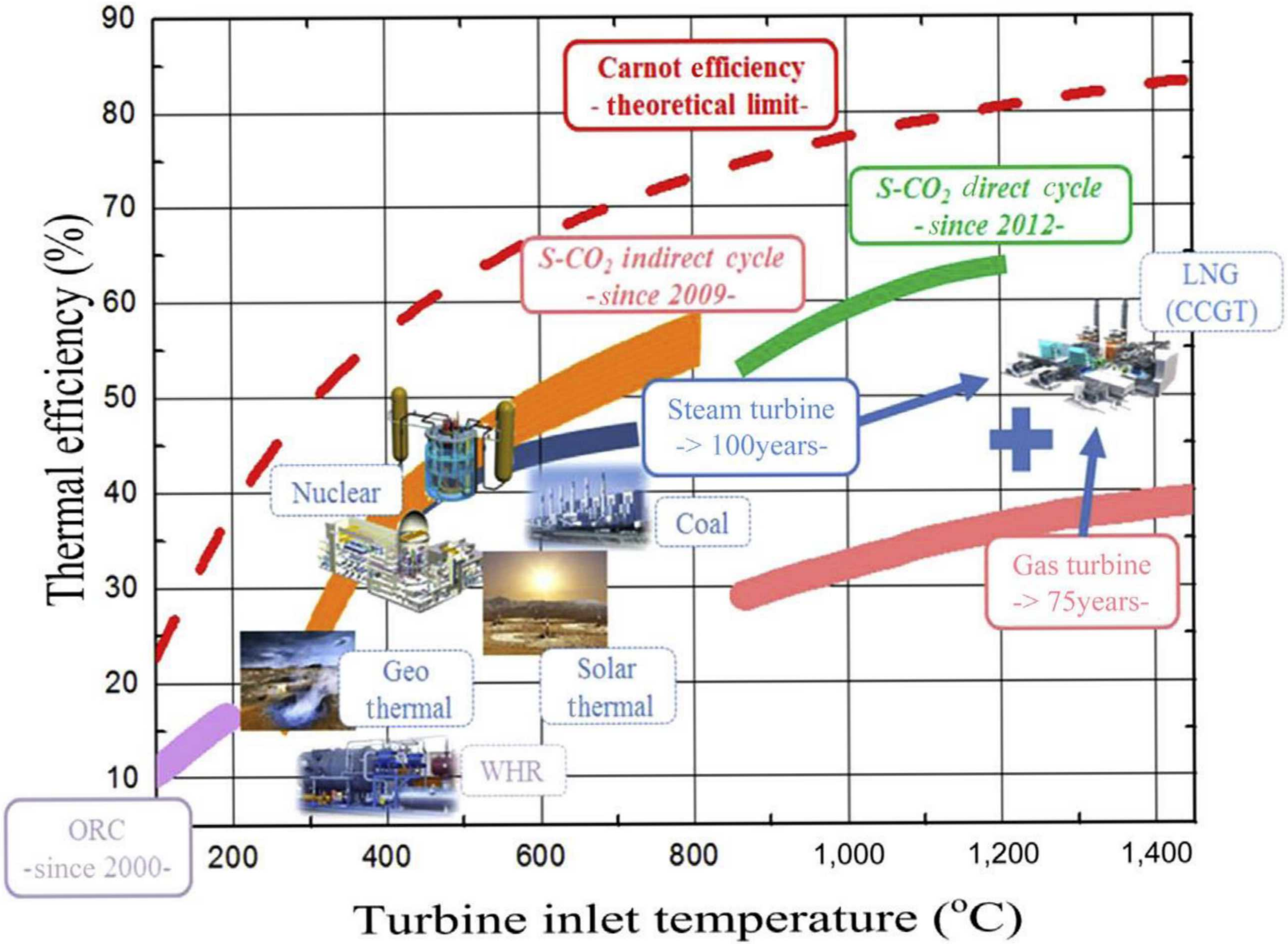
Development sCO2 Power Cycles

Progress Toward Commercial Deployment of sCO2 Brayton Power Cycles

The sCO2 Brayton Cycle [1]

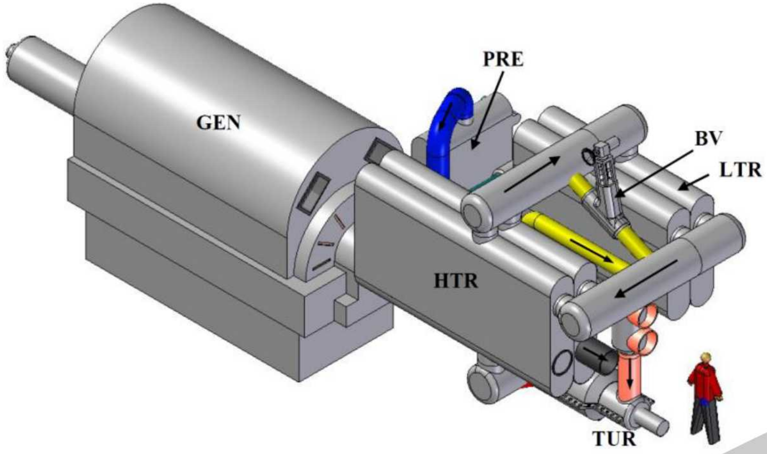


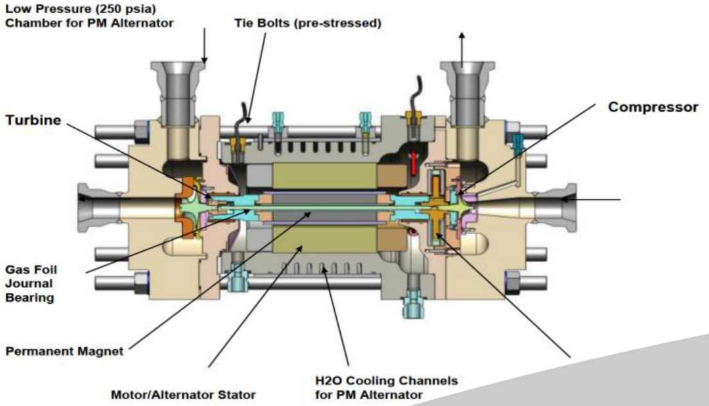
Comparison to Other Power Cycles [2]

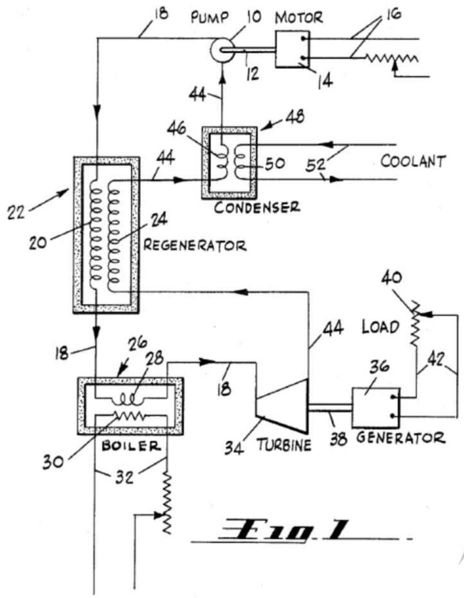


Critical Milestones in sCO2 R&D

1985
Heatric







1963
Cycle Concept

1997
Research Revival

2007
Prototypes
First sCO2 Symposium

2013
Widespread Interest
ASME Turbo Expo Track

[3-6]

Commercially-relevant Pilot Systems

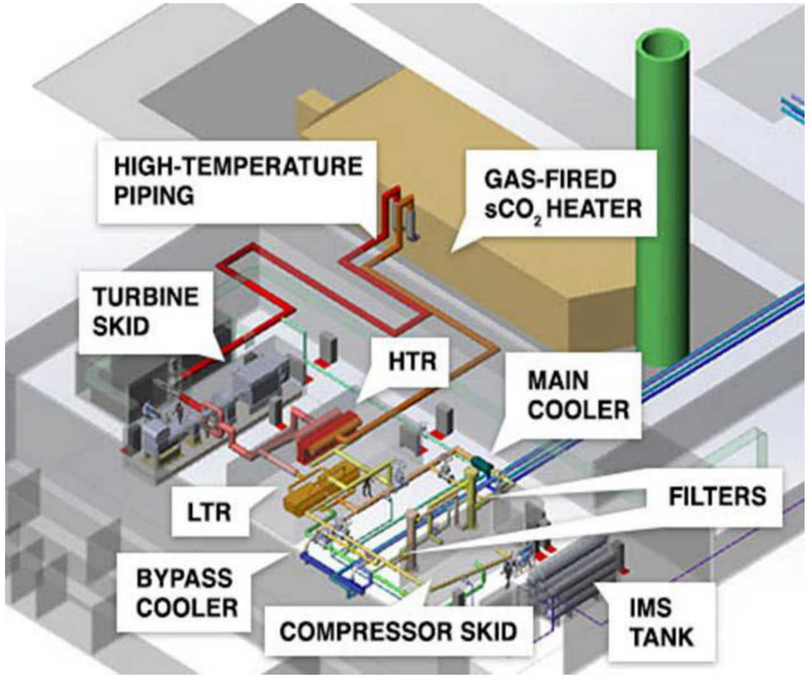
Progress Toward Commercial Deployment of sCO2 Brayton Power Cycles

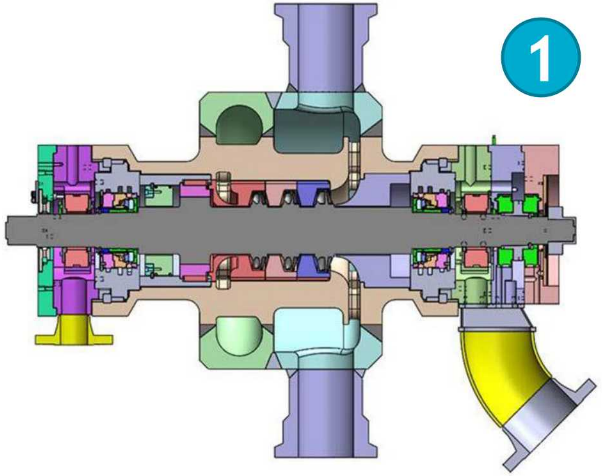
Echogen Power Systems – Akron, Ohio, USA [7,8]

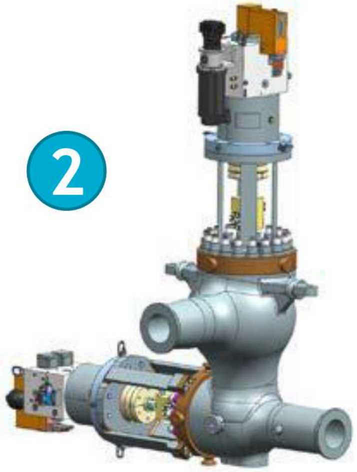
- First commercial sCO2 Brayton power system
- Significant technical milestones including:
  1. Transportable skid-mounted system
  2. 7.3 MW_e design, 3.1 MW_e demonstrated
  3. 16 MW_{th} sCO2 recuperator (200 kW/K)
  4. Validation of design and transient models

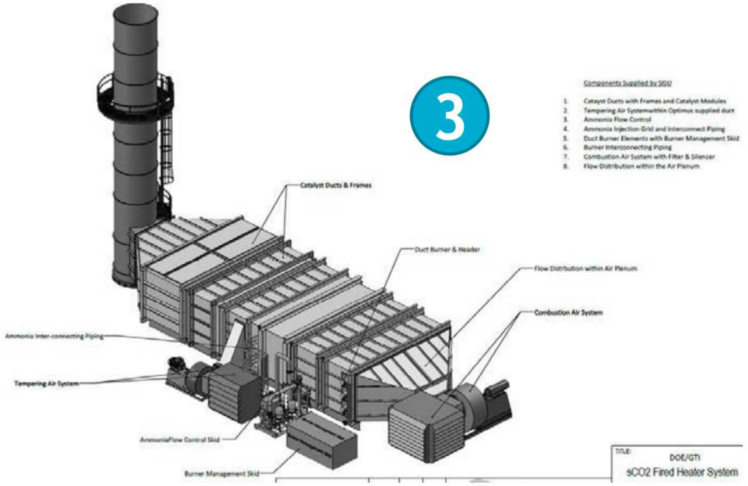
STEP 10 MW_{th} Demonstration – San Antonio, Texas, USA [9]

- Largest indirect-fired sCO2 Brayton cycle
- Significant technical milestones including:
    1. 16 MW_{th} SwRI/GE turbine design
    2. 700 °C 740H turbine stop/control valve
    3. 715 °C 740H gas-fired heater
    4. Scheduled for operation in 2021



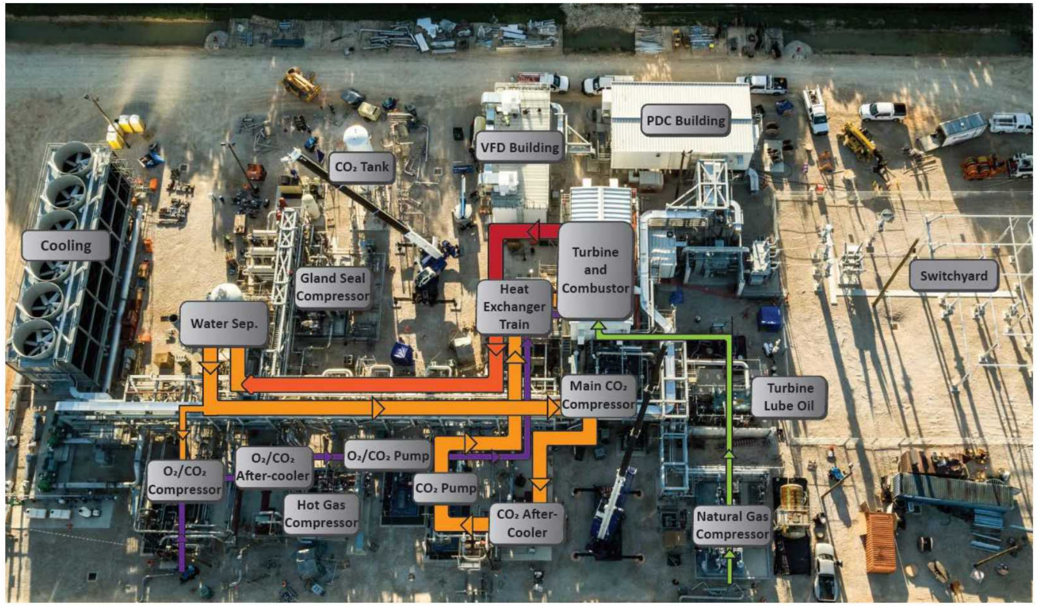


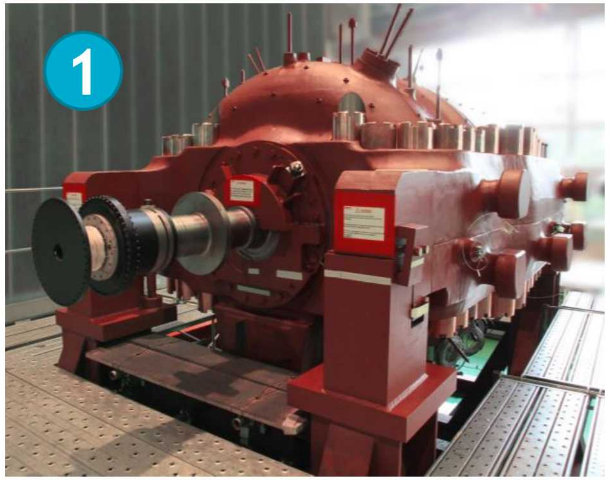


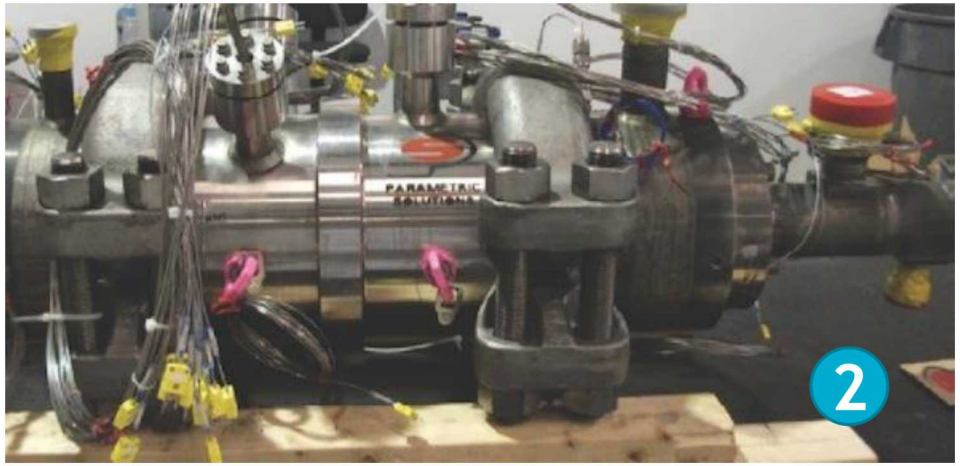


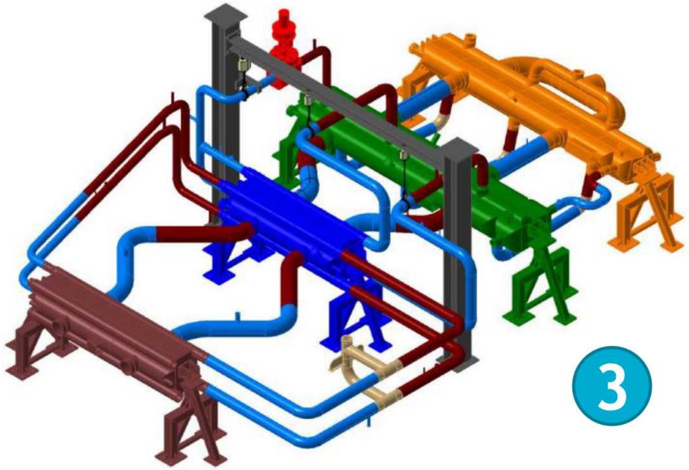
NET Power 50 MW_{th} Demonstration – La Porte, Texas, USA [10-13]

- Largest sCO2 Brayton power system
- Significant technical milestones including:
    1. 50 MW_{th} Toshiba turbine
    2. High pressure oxyfuel combustor
    3. Alloy 617 diffusion bonded heat exchanger
    4. First fire on 2018-05-30









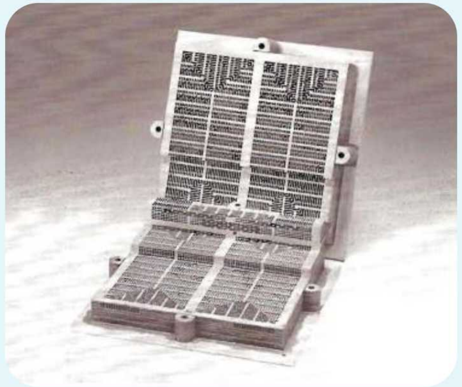
Ongoing Research and Future Plans

Progress Toward Commercial Deployment of sCO2 Brayton Power Cycles

R&D to Reduce the Cost of Heat Exchangers

Design [14,15]

Chemically Milled
Diffusion Bonded



Chemically Blanked
Diffusion Bonded

Micro-Tube and Shell

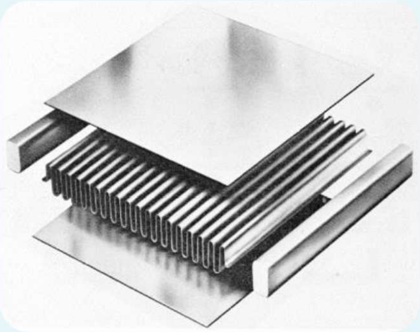
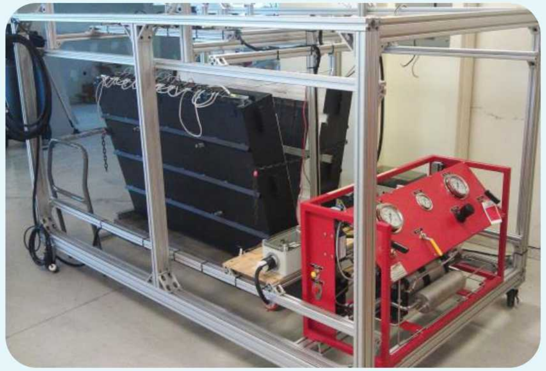


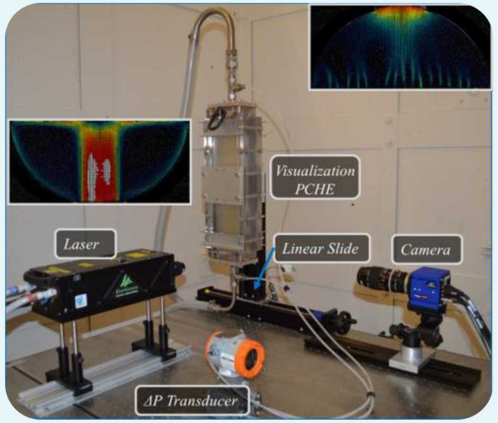
Plate-Fin

Testing [16]

Pressure Fatigue



Thermal Fatigue & Creep

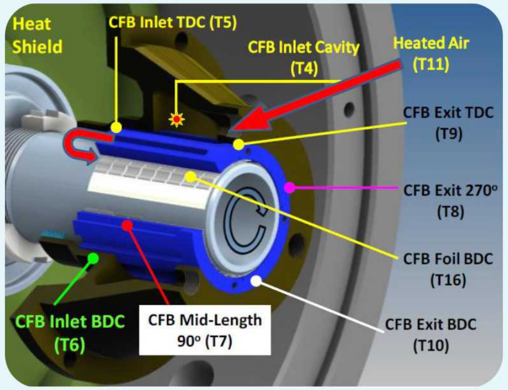


Flow Distribution

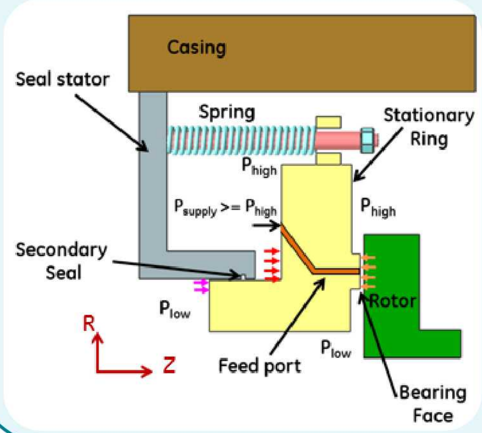
Performance

R&D to Increase the Reliability of Turbomachinery Systems

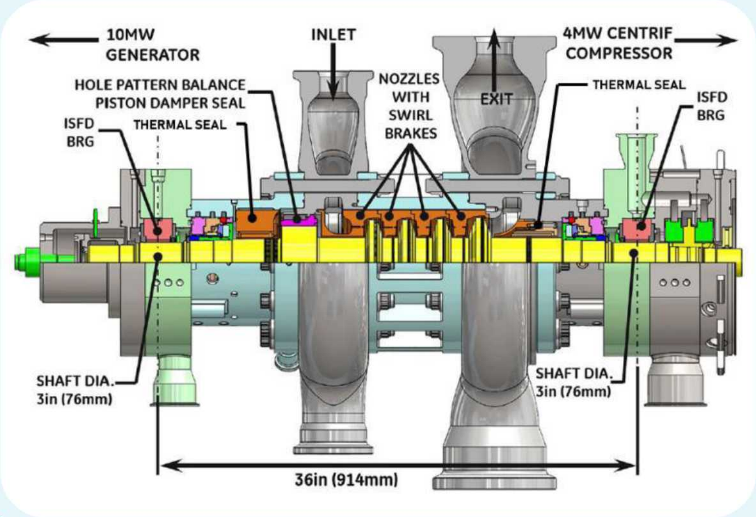
Bearings [17]

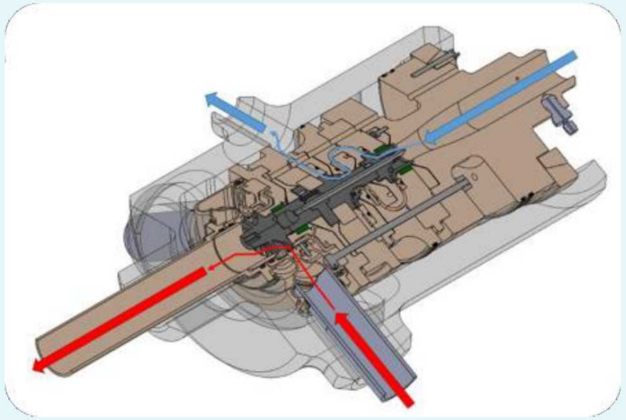


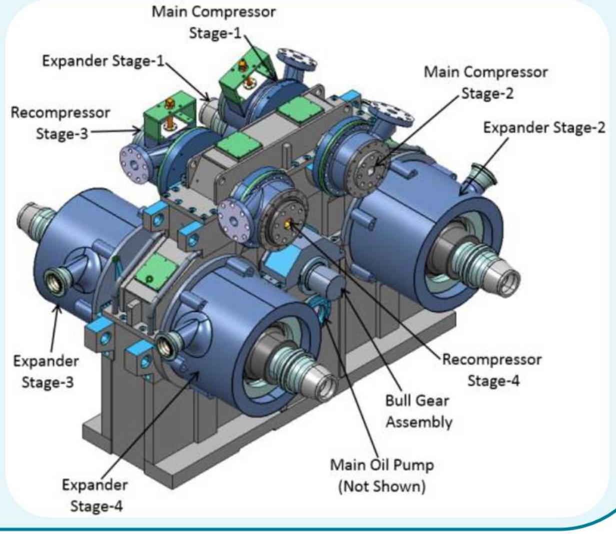
Seals [18]



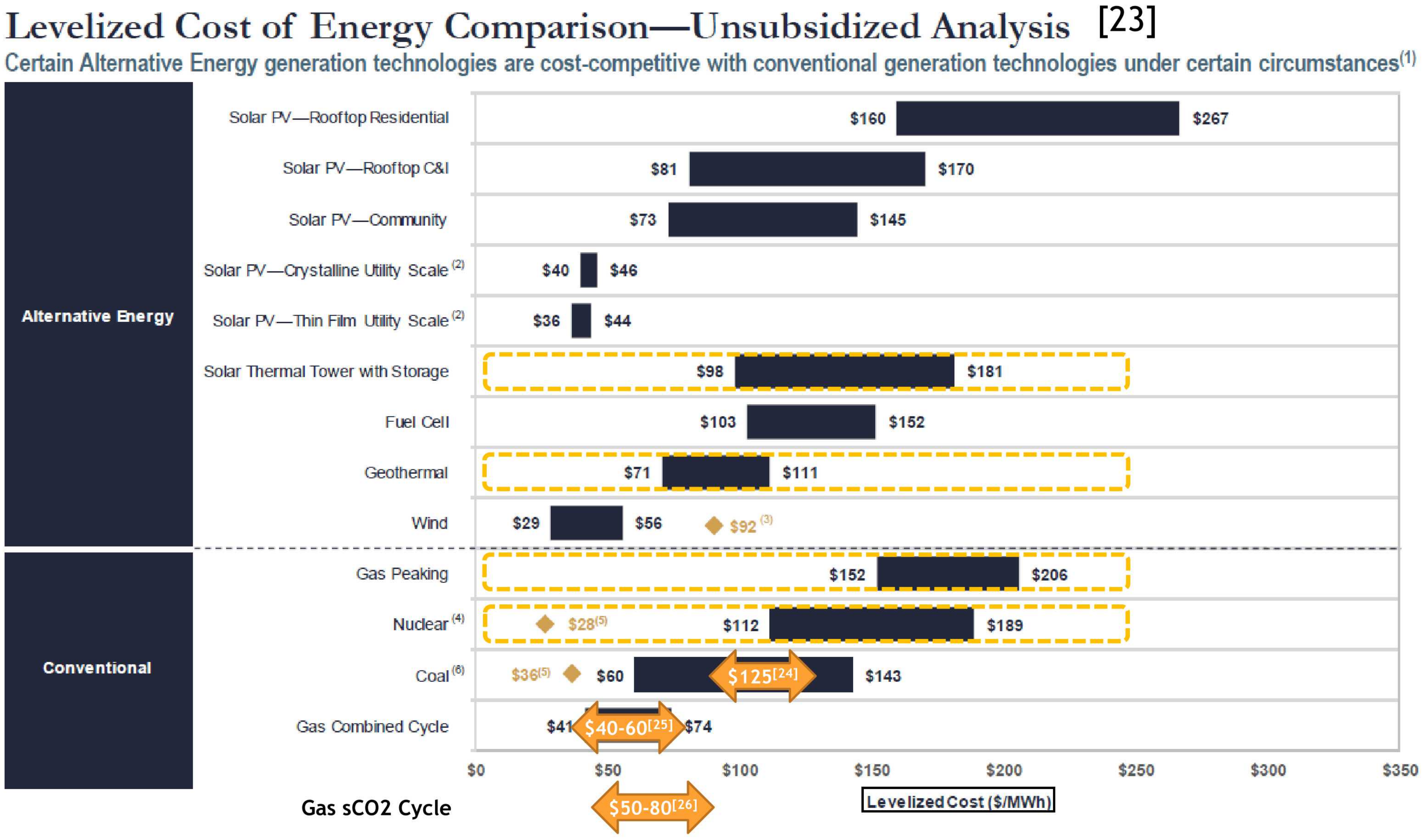
Integration [19-21]







Technoeconomic Studies for First Available Markets[22]



More sCO2 Learning Opportunities

Progress Toward Commercial Deployment of sCO2 Brayton Power Cycles

More to learn about sCO2 Research at SolarPACES 2019

Draft Program Overview SolarPACES 2019 (5th August 2019)

Tuesday, October 1, 2019

	Room 325
08:00	
08:30	Registration (ongoing)
09:00	Opening Session
10:10	Coffee Break
10:40	CSP Market & Projects
12:40	Lunch
14:00	CSP-PV Hybrids
15:30	Coffee Break
16:00	CSP Dispatching
17:30	Poster Session (1)
19:00	Welcome Reception
20:30	

Wednesday, October 2, 2019

Time	Room 325	Room 320	Room 321	Room 322
08:00				
08:30	CSP Technology Innovation (Room 325)			
10:10	Coffee Break			
10:40	Central Receiver Systems	Thermal Energy Storage	Parabolic Trough Systems	Commercial Projects
12:40	Lunch			
14:00	Central Receiver Systems (1)	Thermal Energy Storage	Power Cycles (6)	Hybridization
16:00	Coffee Break			
16:30	Central Receiver Systems	Thermal Energy Storage (1)	Power Cycles (2)	Policy & Marketing
18:30	Poster Session (2)			
19:30	Gala Dinner			

Thursday, October 3, 2019

Time	Room 325	Room 320	Room 321	Room 322
08:00				
08:30	Central Receiver Systems	Measurement Systems	Water Consumption Management	CSP-PV Hybrids
10:10	Coffee Break			
10:40	Central Receiver Systems	Measurement Systems	Reliability & Service Life	Heat Transfer Fluids
12:40	Lunch			
14:00	Process Heat	Thermochemical Energy Storage	Reliability & Service Life	Advanced Materials & Manufacturing (1)
16:00	Coffee Break			
16:30	Emerging Concepts	Thermal Energy Storage	Software Tools	Solar Fuels
18:30	Poster Session (1)			

Friday, October 4, 2019

Time	Room 325	Room 320	Room 321	Room 322
08:00				
08:30	Central Receiver Systems	Solar Resource Assessment	Water Desalination & Detoxification	Solar Fuels
10:10	Coffee Break			
10:40	Central Receiver Systems	Solar Resource Assessment	Reliability & Service Life	Solar Fuels
12:40	Lunch			
14:00	Closing Session (Room 325)			
16:00				

Future Conferences with an sCO2 R&D Focus

7th International sCO_2 Power Cycles Symposium – 2020

Tutorial Sessions: March 30, 2020

Conference: March 31-April 2, 2020

Reference Slides

Progress Toward Commercial Deployment of sCO2 Brayton Power Cycles

Works Cited

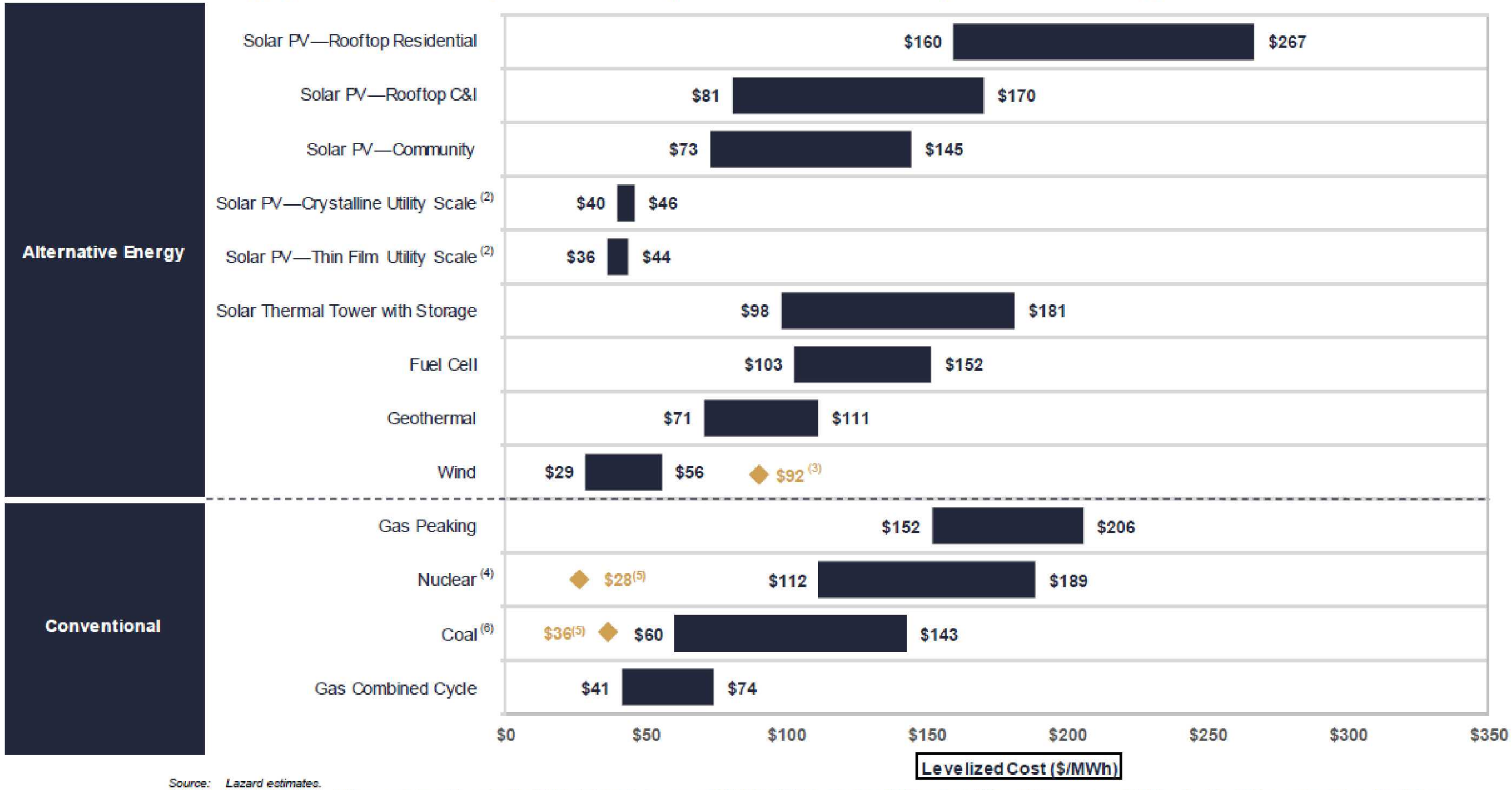
1. E. J. Parma, S. A. Wright, M. E. Vernon, D. D. Fleming, G. E. Rochau, A. J. Suo-Anttila, A. Al Rashdan, and P. V. Tsvetkov, “Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept,” Sandia National Laboratories, Albuquerque, NM, USA, SAND 2011-2525, May 2011.
2. Y. Ahn, S. J. Bae, M. Kim, S. K. Cho, S. Baik, J. I. Lee, and J. E. Cha, “Review of supercritical CO2 power cycle technology and current status of research and development,” Nucl. Eng. Technol., vol. 47, no. 6, pp. 647–661, Oct. 2015.
3. E. G. Feher, “Supercritical Cycle Heat Engine,” 323740301-Mar-1966.
4. Stephen John Dewson, “Printed Circuit Heat ExchangersforSupercritical CO2 Cycles,” presented at the Symposium on Supercritical CO2 Power Cycle for Next Generation Systems, Cambridge, Massachusetts, USA, 06-Mar-2007.
5. J. P. Gibbs, P. Hejzlar, and M. J. Driscoll, “Applicability of Supercritical CO2 Power Conversion Systems to GEN IV Reactors,” Center for Advanced Nuclear Energy Systems MIT Department of Nuclear Science and Engineering, Cambridge, MA, Topical Report MIT-GFR-037, Sep. 2006.
6. S. A. Wright, T. M. Conboy, and G. E. Rochau, “Break-even Power Transients for two Simple Recuperated S-CO2 Brayton Cycle Test Configurations,” in SCO2 Power Cycle Symposium, Boulder, Colorado, 2011.
7. Timothy J. Held, “Initial Test Results of a Megawatt-Class Supercritical CO2 Heat Engine,” in The 4th International Symposium - Supercritical CO2 Power Cycles, Pittsburgh, Pennsylvania, 2014, pp. 1–12.
8. Vamshi K. Avadhanula, Luke R. Magyar, and Timothy J. Held, “Printed Circuit Heat Exchanger and Finned-Tube Heat Exchanger Modeling for a Supercritical CO2 Power Cycle,” presented at the The 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, Pennsylvania, USA, 2018.
9. John Marion, Mike Kutin, Aaron McClung, Jason Mortzheim, and Robin Ames, “The STEP 10 MWe sCO2 Pilot Plant Demonstration,” in Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, Phoenix, AZ, USA, 2019, pp. 1–8.
10. Rodney J Allam, “NET Power’s CO2 cycle: the breakthrough that CCS needs,” Modern Power Systems, 10-Jul-2013.
11. R. Allam, S. Martin, B. Forrest, J. Fetvedt, X. Lu, D. Freed, G. W. Brown, T. Sasaki, M. Itoh, and J. Manning, “Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture,” Energy Procedia, vol. 114, pp. 5948–5966, Jul. 2017.
12. Mike McGroddy, “NET Power,” presented at the Carbon Management Workshop, Midland, Texas, USA, 04-Dec-2017.
13. Toshiba, “Toshiba Ships Turbine for World’s First Direct-Fired Supercritical Oxy-Combustion CO2 Power Cycle Demonstration Plant to U.S.,” Toshiba, 01-Nov-2016. [Online]. Available: https://www.toshiba.co.jp/about/press/2016_11/pr0101.htm.
14. G. O. Musgrove, C. Pittaway, E. Vollnogle, and L. Chordia, “Tutorial: Heat Exchangers for Supercritical CO2 Power Cycle Applications,” presented at the ASME Turbo Expo 2014, Dusseldorf, Germany, 16-Jun-2014.
15. J. E. Hesselgreaves, Compact heat exchangers : selection, design and operation. Amsterdam: Pergamon, 2001.
16. G. O. Musgrove, J. Carrero, and S. Sullivan, “Tutorial: Heat Exchangers for Supercritical CO2 Power Cycle Applications,” presented at the ASME Turbo Expo 2015, Montreal, Canada, 15-Jun-2015.
17. Hooshang Heshmat, James F. Walton II, and Brian D. Nicholson, “Ultra-High Temperature Compliant Foil Bearings – the Journey to 870°C and Application in Gas Turbine Engines: Experiment,” in Proceedings of ASME Turbo Expo 2018 Turbomachinery Technical Conference and Exposition, Oslo, Norway, 2018, pp. GT2018–75555.
18. Deepak Trivedi, Rahul A. Bidkar, Chris Wolfe, and Xiaoqing Zheng, “Film-Stiffness Characterization for Supercritical CO2 Film-Riding Seals,” in Proceedings of ASME Turbo Expo 2018 Turbomachinery Technical Conference and Exposition, Oslo, Norway, 2018, pp. GT2018–76161.
19. Stefan D. Cich, J. Jeffrey Moore, Michael Marshall, Kevin Hoopes, Jason Mortzheim, and Douglas Hofer, “RADIAL INLET AND EXIT DESIGN FOR A 10 MWe sCO2 AXIAL TURBINE,” in Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, Phoenix, AZ, USA, 2019, pp. 1–10.
20. Jim Pasch and David Stapp, “Testing of a New Turbocompressor for Supercritical Carbon Dioxide Closed Brayton Cycles,” in Proceedings of ASME Turbo Expo 2018 Turbomachinery Technical Conference and Exposition, Oslo, Norway, 2018, pp. GT2018–77044.
21. Timothy C. Allison, Natalie R. Smith, Robert Pelton, Sewoong Jung, and Jason C. Wilkes, “Experimental Validation of a Wide-Range Centrifugal Compressor Stage for Supercritical CO2 Power Cycles,” in Proceedings of ASME Turbo Expo 2018 Turbomachinery Technical Conference and Exposition, Oslo, Norway, 2018, pp. GT2018–77026.
22. Nathan T. Weiland, Blake W. Lance, and Sandeep R. Pidaparti, “SCO2 Power Cycle Component Cost Correlations from DOE Data Spanning Multiple Scales and Applications,” in Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, Phoenix, AZ, USA, 2019, pp. 1–17.
23. LAZARD, “Lazard’s Levelized Cost of Energy Analysis - Version 12.0,” Nov. 2018.
24. C. W. White, W. Shelton, N. Weiland, T. Shultz, J. Plunkett, and D. Gray, “Techno-economic Evaluation of Utility-Scale Power Plants Based on the Indirect sCO2 Brayton Cycle,” 21490, 1490272, Dec. 2017.
25. M. Persichilli, A. Kacludis, E. Zdankiewicz, and T. Held, “Supercritical CO2 Power Cycle Developments and Commercialization: Why sCO2 can Displace Steam,” presented at the Power-Gen India & Central Asia 2012, Pragati Maidan, New Delhi, India, 2012, pp. 1–16.
26. Thomas E. Drennen, “Economic Viability of sCO2 Brayton Systems and Market Analysis,” 06-Sep-2019.

More to learn about sCO2 Research at SolarPACES 2019

- Tuesday, Poster Session 1
  - Performance Analysis and Optimization of Particle/sCO2 Fluidized Bed Heat-Exchanger for Next Generation CPS, Dr. Mengda Jia, Tsinghua University
- Wednesday, Session 3-A
  - Testing and Model Validation of a Prototype Moving Packed-Bed Particle-to-sCO2 Heat Exchanger, Dr. Kevin Albrecht, Sandia National Laboratories
- Wednesday, Session 3-C
  - Comparing Line-Focusing and Central Tower Solar Power Plants with s-CO2 Binary Mixture Brayton Power Cycles, Robert Valencia-Chapi, Technical University of Madrid
  - Current Status of the Supercritical CO2 Power Cycle Study in KIER, Dr. Young-Jin Baik, Korea Institute of Energy Research
  - Dynamic Modeling and Transient Analysis of a Recompression Supercritical CO2 Brayton Cycle, Pan Zhou, EDF China
  - Off-Design Performance of CSP Plant Based on Supercritical CO2 Cycles, Dario Alfani, Politecnico di Milano, Presented by Dr. Marco Binotti
  - Shouhang-EDF 10MWe Supercritical CO2 Cycle + CSP Demonstration Project, Pan Zhou, EDF China
  - Thermodynamic Analysis of an Indirect Supercritical CO2 – Air Driven Concentrated Solar Plant with a Packed Bed Thermal Energy Storage, Silvia Trevisan, KTH Royal Institute of Technology
- Wednesday, Session 4-B
  - Pumped Thermal Electricity Storage with Supercritical CO2 Cycles and Solar Heat Input, Dr. Joshua McTigue, National Renewable Energy Laboratory
- Wednesday, Session 4-C
  - An Update on the Status of a Reduced Flow Test of a 10MW 700°C sCO2 Integrally Geared Compander, Jason Wilkes, Rotating Machinery Group
  - Guidelines for the Design and Operation of Supercritical Carbon Dioxide R&D Systems, Matthew Carlson, Sandia National Laboratories
- Wednesday, Poster Session 2
  - Supercritical CO2 (sCO2) Power Cycle with Heat Pump Heat Sink, Hafiz Ali Muhammad, Korea University of Science and Technology
  - Numerical Study of Fluidized Bed Particle/sCO2 Heat Transfer, Dr. Chao Wang, Tsinghua University
- Thursday, Session 3-D
  - Development of Nickel Superalloy Inconel Alloy 740H for uSCO2 Power Cycles and Molten Salt Receivers Operating Between 600˚C to 800˚C, Dr. Stephen McCoy, Special Metals Corporation
- Thursday, Poster Session 3
  - Performance Analysis of Supercritical CO2 Cycles for CSP, Dhinesh Thanganadar, Cranfield University

Levelized Cost of Energy Comparison—Unsubsidized Analysis

Certain Alternative Energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances[1]



Source: *Lazard estimates.*

Note: Here and throughout this presentation, unless otherwise indicated, the analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost. Please see page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities.

(1) Such observation does not take into account other factors that would also have a potentially significant effect on the results contained herein, but have not been examined in the scope of this analysis. These additional factors, among others, could include: import tariffs; capacity value vs. energy value; stranded costs related to distributed generation or otherwise; network upgrade, transmission, congestion or other integration-related costs; significant permitting or other development costs, unless otherwise noted; and costs of complying with various environmental regulations (e.g., carbon emissions offsets or emissions control systems). This analysis also does not address potential social and environmental externalities, including, for example, the social costs and rate consequences for those who cannot afford distribution generation solutions, as well as the long-term residual and societal consequences of various conventional generation technologies that are difficult to measure (e.g., nuclear waste disposal, airborne pollutants, greenhouse gases, etc.).

(2) Unless otherwise indicated herein, the low end represents a single-axis tracking system and the high end represents a fixed-tilt design.

(3) Represents the estimated implied midpoint of the LCOE of offshore wind, assuming a capital cost range of approximately $2.25 – $3.80 per watt.

(4) Unless otherwise indicated, the analysis herein does not reflect decommissioning costs or the potential economic impacts of federal loan guarantees or other subsidies.

(5) Represents the midpoint of the marginal cost of operating fully depreciated coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned coal plant is equivalent to the decommissioning and site restoration costs. Inputs are derived from a benchmark of operating, fully depreciated coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper and lower quartile estimates derived from Lazard's research. Please see page titled "Levelized Cost of Energy Comparison—Alternative Energy versus Marginal Cost of Selected Existing Conventional Generation" for additional details.

(6) Unless otherwise indicated, the analysis herein reflects average of Northern Appalachian Upper Ohio River Barge and Pittsburgh Seam Rail coal. High end incorporates 90% carbon capture and compression. Does not include cost of transportation and storage.