GTEN 2021 Virtual Symposium

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Carbon Capture and Industrial Gas Turbines

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Increasing Carbon Pricing Initiatives - Tax / Trade / Credits

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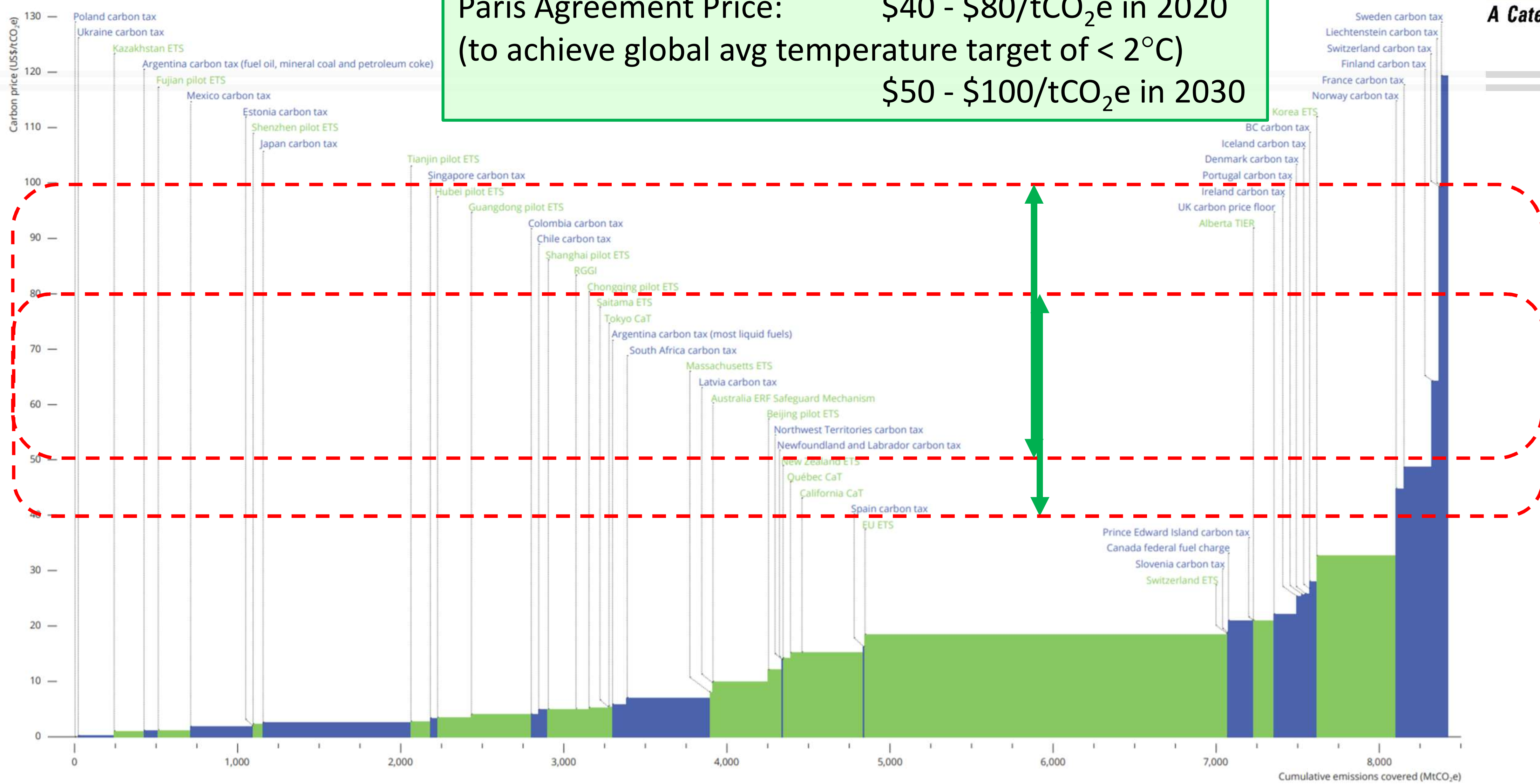
Paris Agreement Price: $40 - $80/t$CO_2$e in 2020
(to achieve global avg temperature target of < 2°C)
$50 - $100/t$CO_2$e in 2030

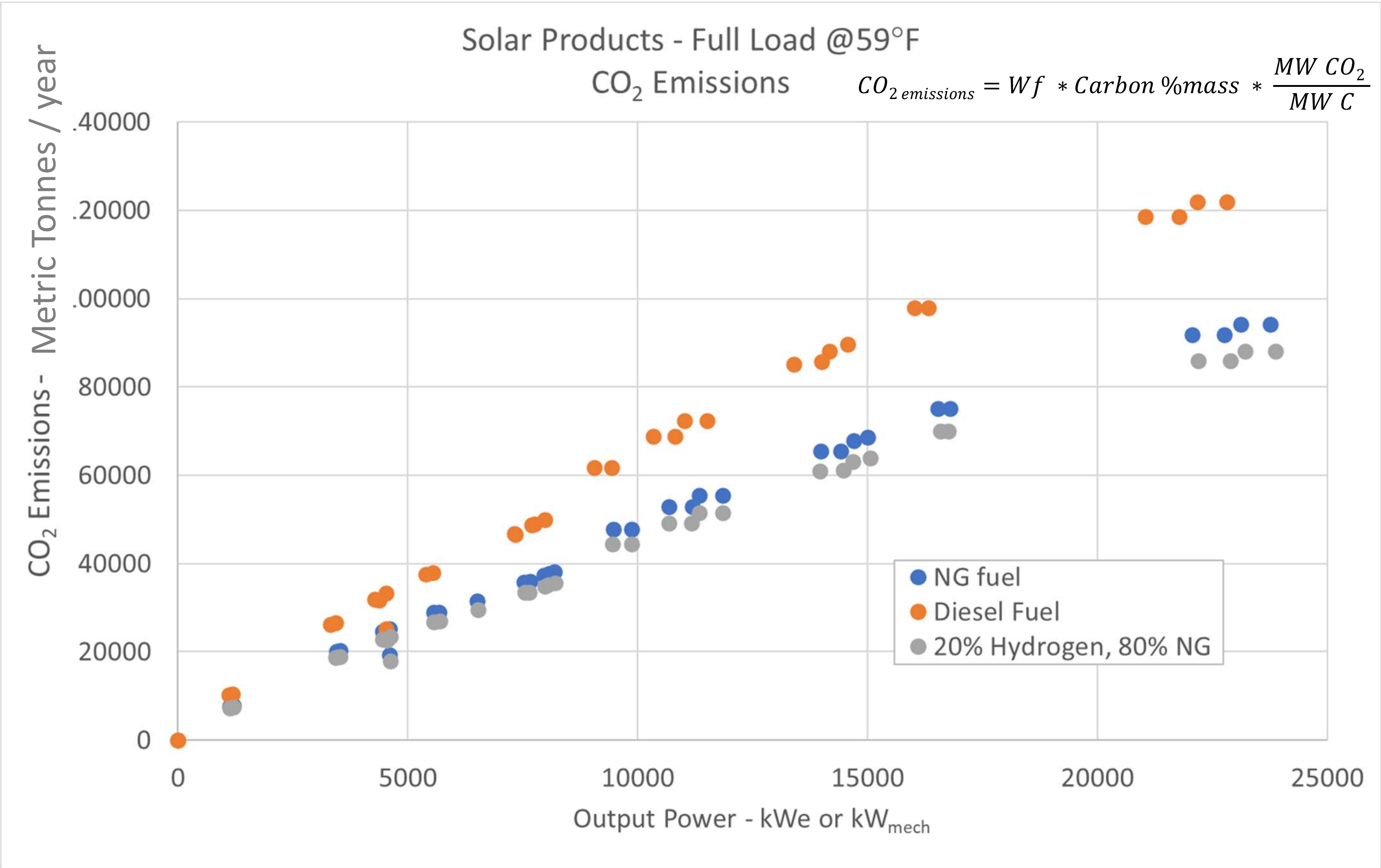


Note: The British Columbia GGIRCA, Canada federal OBPS, Kazakhstan ETS, Nova Scotia CaT, Newfoundland and Labrador PSS, Saskatchewan OBPS, and Washington CAR are not shown in this graph as price information is not available for those initiatives. The carbon tax rate applied in Argentina, Finland, Ireland, Mexico and Norway varies with the fossil fuel type and use. The carbon tax rate applied in Denmark and Iceland varies with the GHG type. The graph shows the average carbon tax rate weighted by the amount of emissions covered at the different tax rates in those jurisdictions.

ETS Carbon tax

*Source – World Bank Group, State and Trends of Carbon Pricing 2020

CO_2 Emissions of Gas Turbine Products



Carbon Capture Equipment

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- Traditionally, carbon capture has been with the amine process
  – CO_2 absorbed into a liquid, then heated to drive off CO_2
  – High capital cost of equipment a disadvantage with Solar engines, better with bigger systems
- Efforts mostly on mole sieve capture
  – Adsorption process, smaller and less expensive than the amine system, better with smaller systems
- In both cases:
  – The absorber / adsorption bed size/cost scales with the inverse square root of the purity based on constant velocity and dwell time
  – The amount of CO_2 that can be captured is linear with the concentration, or 7X greater at 21% CO_2 than 3% CO_2

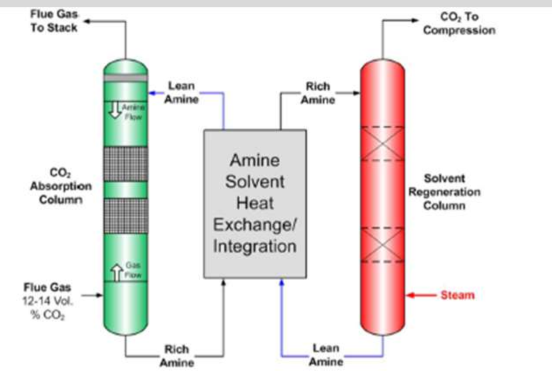

Figure 24 Amine Carbon Capture Process (from DOE/NETL)

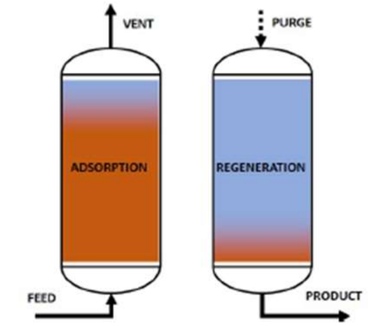

Figure 26 Multi-Bed Adsorption (Mole Sieve) Capture Process

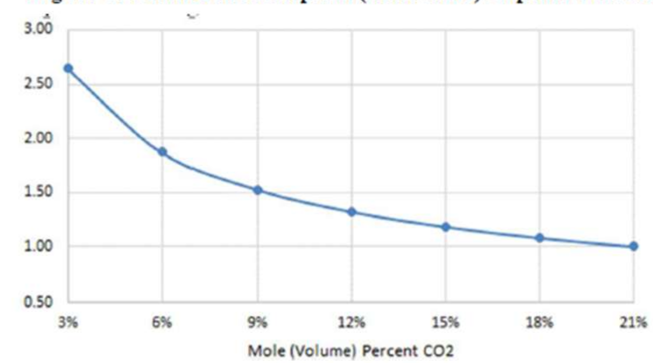

Figure 25 Normalized Absorber Diameter vs. CO_2 Inlet Purity

Carbon Capture Economics

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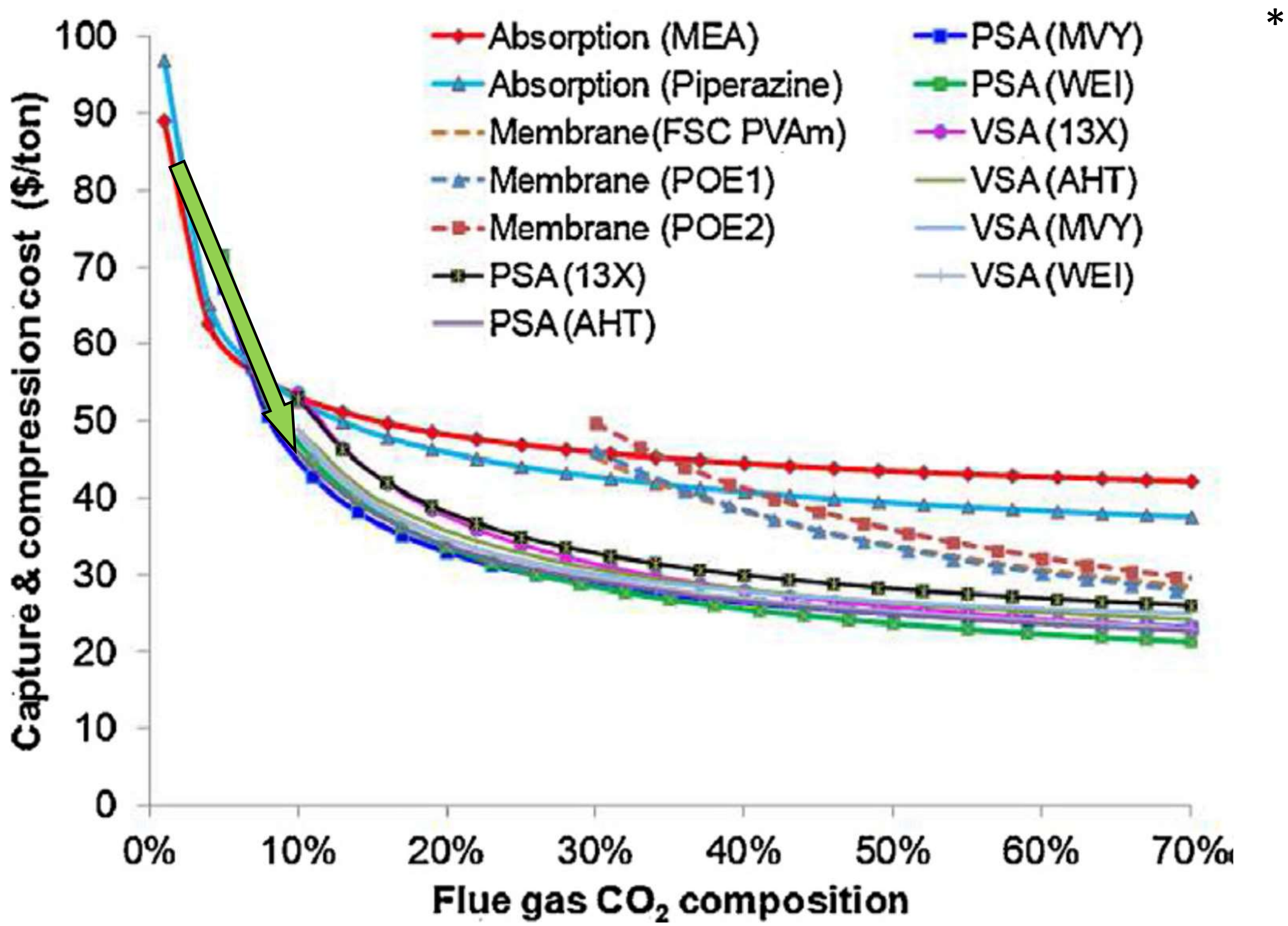
- Gas turbines have about 3% molar fraction of CO_2 concentration in the exhaust
- To make CC economical the concentration of CO_2 is essential
- Exhaust Gas Recirculation (EGR) is an enabler to increase CO_2 concentration in the exhaust of a gas turbine



*Source – M.M. Faruque Hasan, Eric L. First, Fani Boukouvala, Christodoulos A. Floudasa, A multi-scale framework for CO2 capture, utilization, and sequestration: CCUS and CCU, Journal of Computers and Chemical Engineering, May 2015

Simulation of Overall Gas Turbine Engine System with Exhaust Gas Recirculation (EGR)

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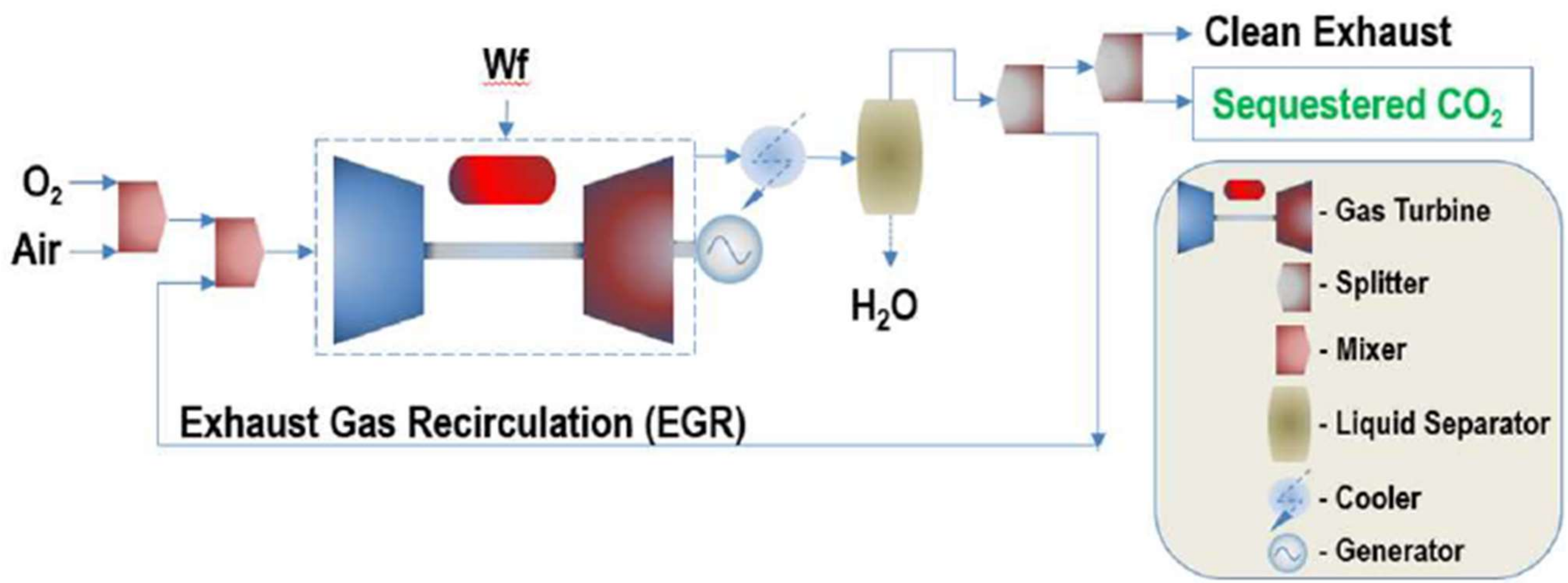
- Detailed Accounting
  - Part Load Controls
    DLE and conventional
  - Thermal analysis
  - Gas/liquid constituents
  - Non-dimensional behavior
  - EGR levels
  - O_2 supplementation



Considerations for EGR Optimization

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- Recycling exhaust gas (high CO_2, lower O_2) into gas turbine inlet
- Effect of non-dimensional characterizations, especially the compressor
- Part load operation for different combustion systems DLE and conventional
- Minimize cost while maximizing performance and CO_2 capture
- Must cool exhaust…
  - Leverage waste heat to maximize utilization of fuel energy, consider bottoming cycles
  - Capture and use condensing water in the exhaust

Bottoming Cycles - Reduce Carbon Intensity

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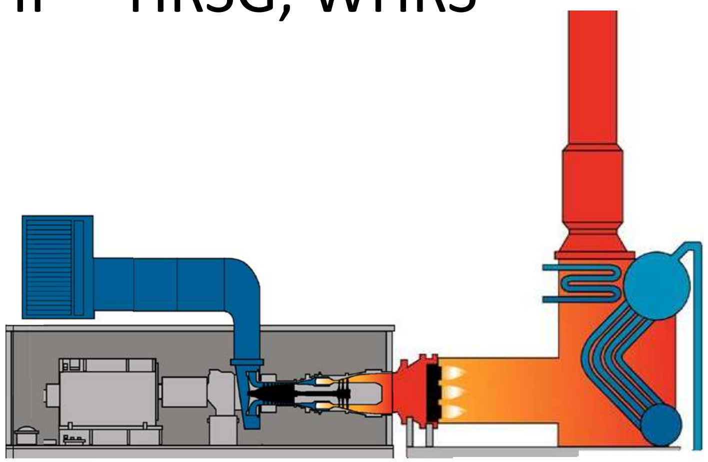
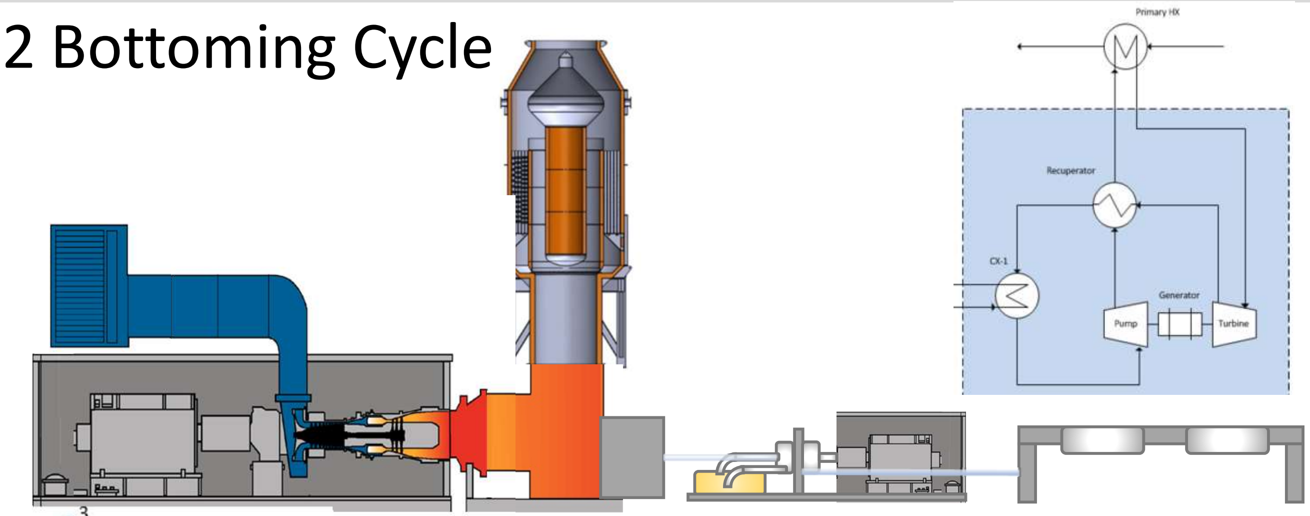
CHP – HRSG, WHRS



sCO2 Bottoming Cycle

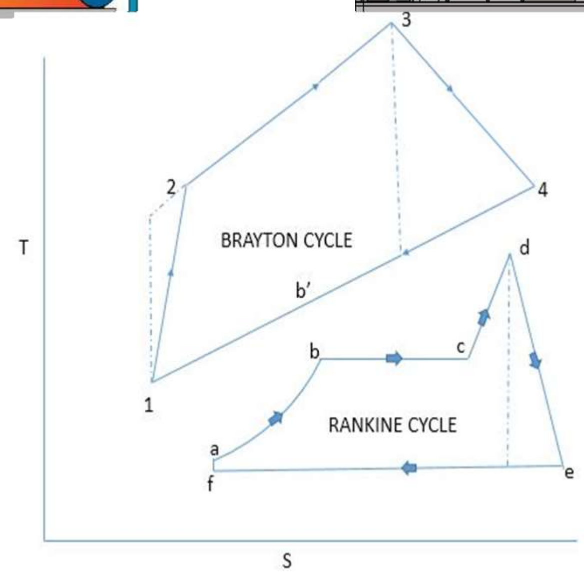


Steam Generator

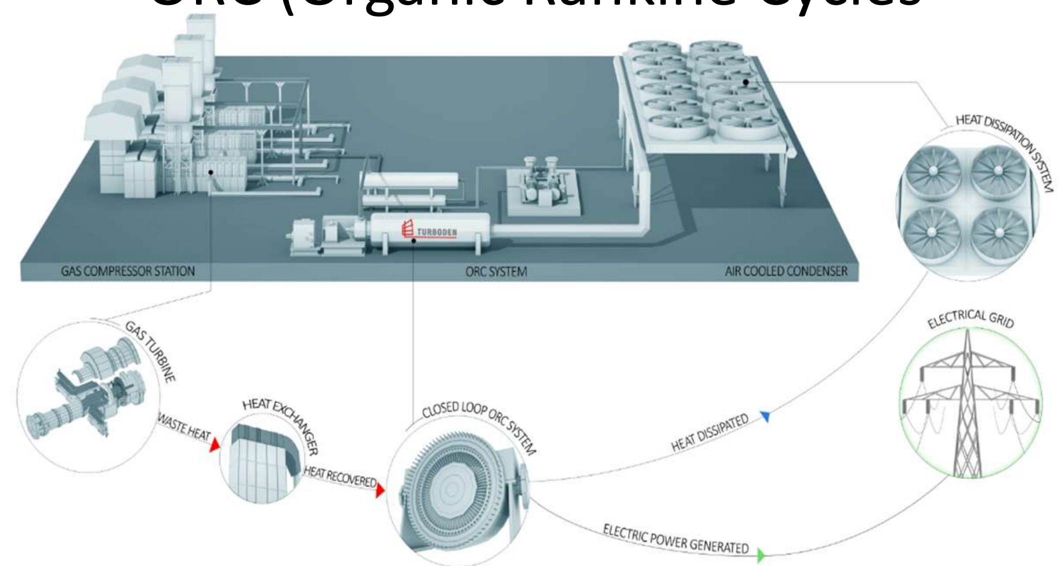
Utility steam turbines from 90 to 1,900 MW

Industrial steam turbines from 2 to 250 MW

Dresser-Rand steam turbines from <10 kW to 25 MW



ORC (Organic Rankine Cycles



Parametric Analysis with EGR System Model

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- Power improves with EGR
- Efficiency same or less
- Hot End Drive (HED) improves more than the Cold End Drive (CED)

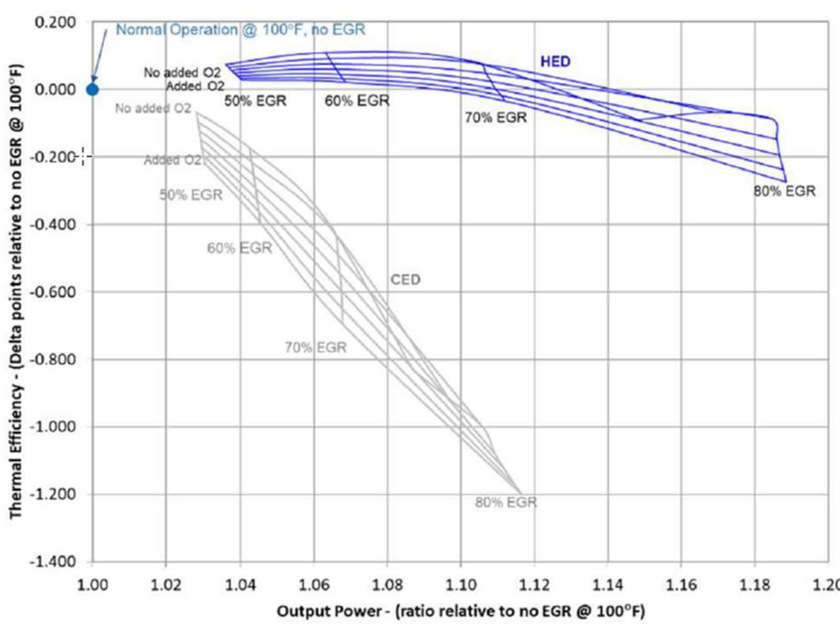

Figure 8. HED EGR Parametric with 100°F inlet – Relativized Thermal Eff vs Power (CED in gray for comparison)

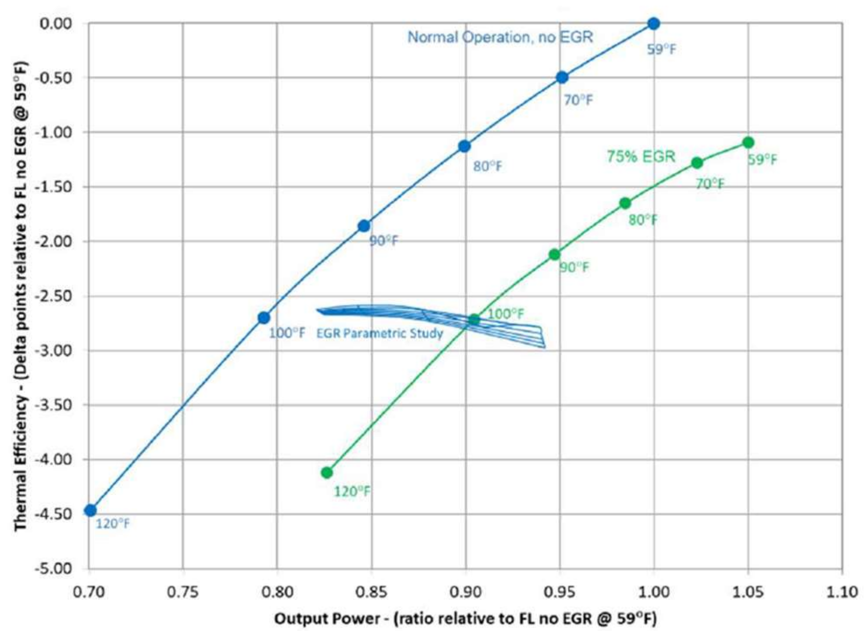

Figure 9. HED Ambient Temperature Lapse Rate with and without EGR – Relativized Thermal Eff vs Power

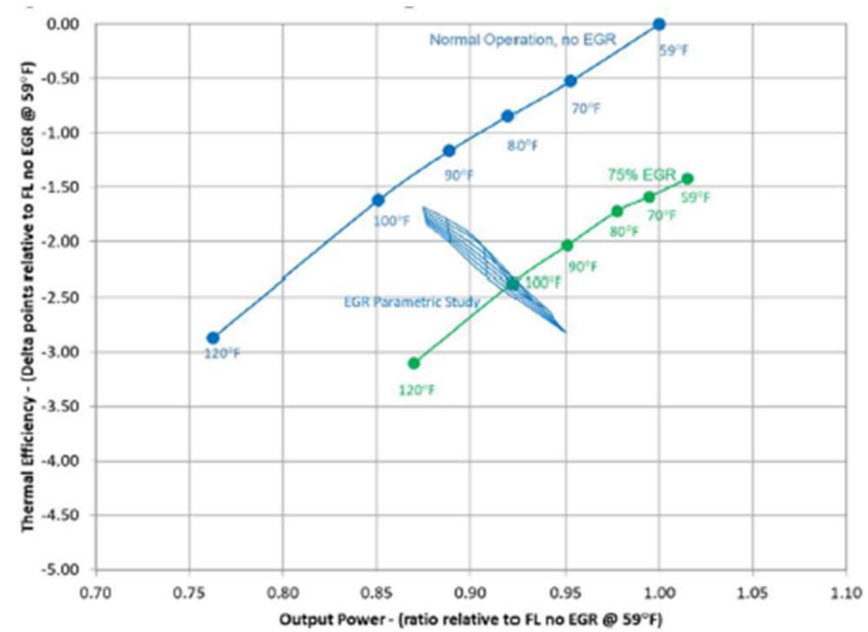

Figure 3. CED Ambient Temperature Lapse Rate with and without EGR – Relativized Thermal Eff vs Power

Parametric Analysis with EGR System Model

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- Minimum required O_2 levels determined by combustion analysis
- CO_2 molar fraction levels and exhaust flow set by amount of EGR

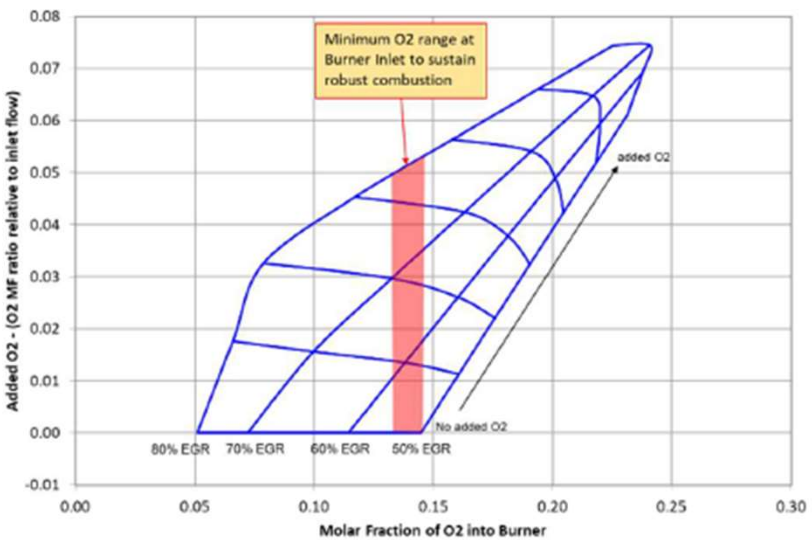

Figure 4. CED EGR Parametric with 100°F inlet – Supplemental O_2 vs O_2 MF into the burner

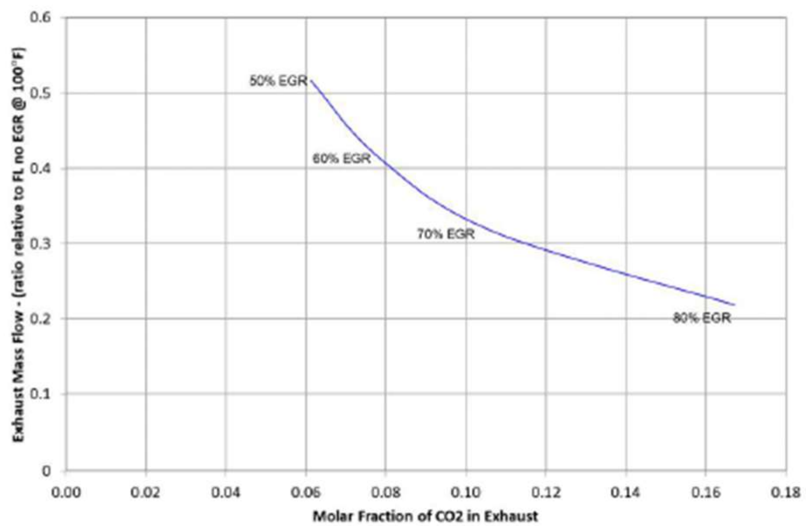

Figure 6. CED EGR Parametric with 100°F inlet – Exhaust mass flow vs Exhaust CO_2 MF

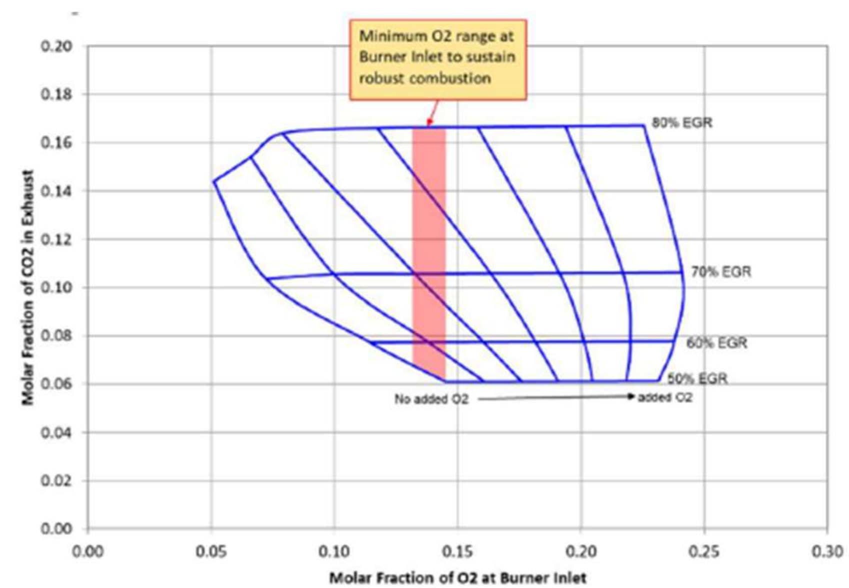

Figure 5. CED EGR Parametric with 100°F inlet – Exhaust CO_2 vs O_2 MF into the burner

Parametric Analysis with EGR System Model

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- Full Load Analysis Results – Power and Thermal Efficiency
- O_2 addition to set combustion inlet conditions at least ~15% O_2 MF

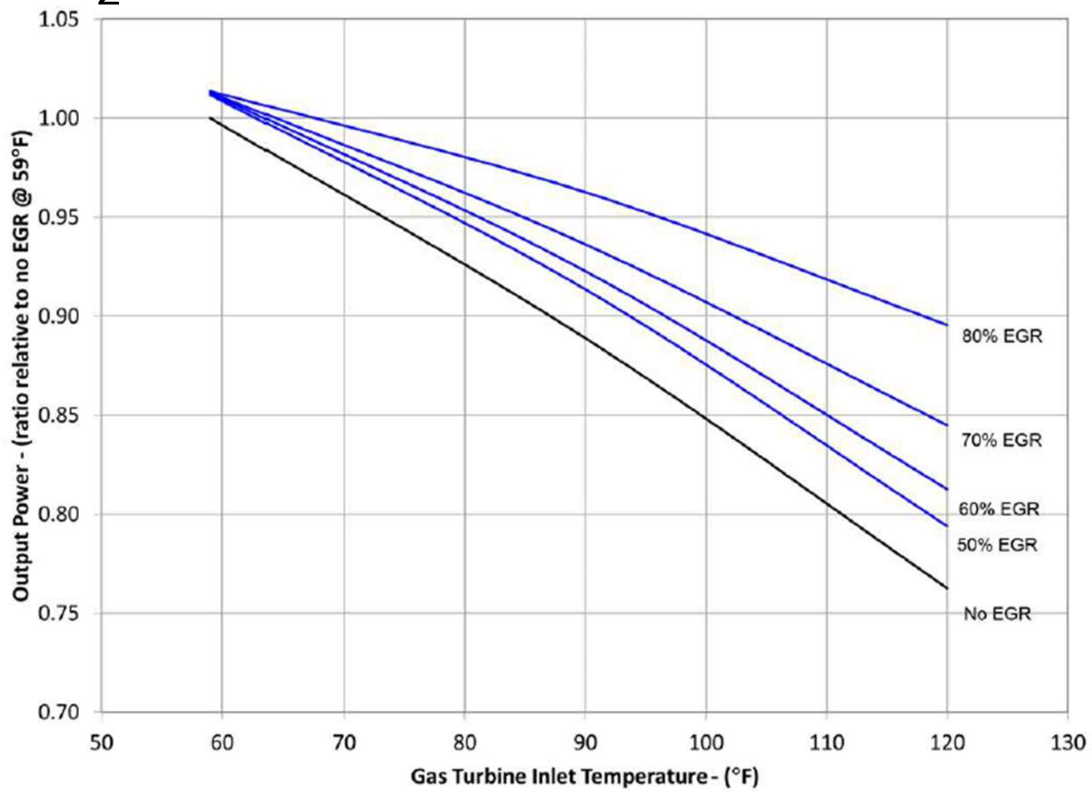

Figure 2. Full Load @ Constant EGR Levels – Relativized Power vs Inlet Temperature

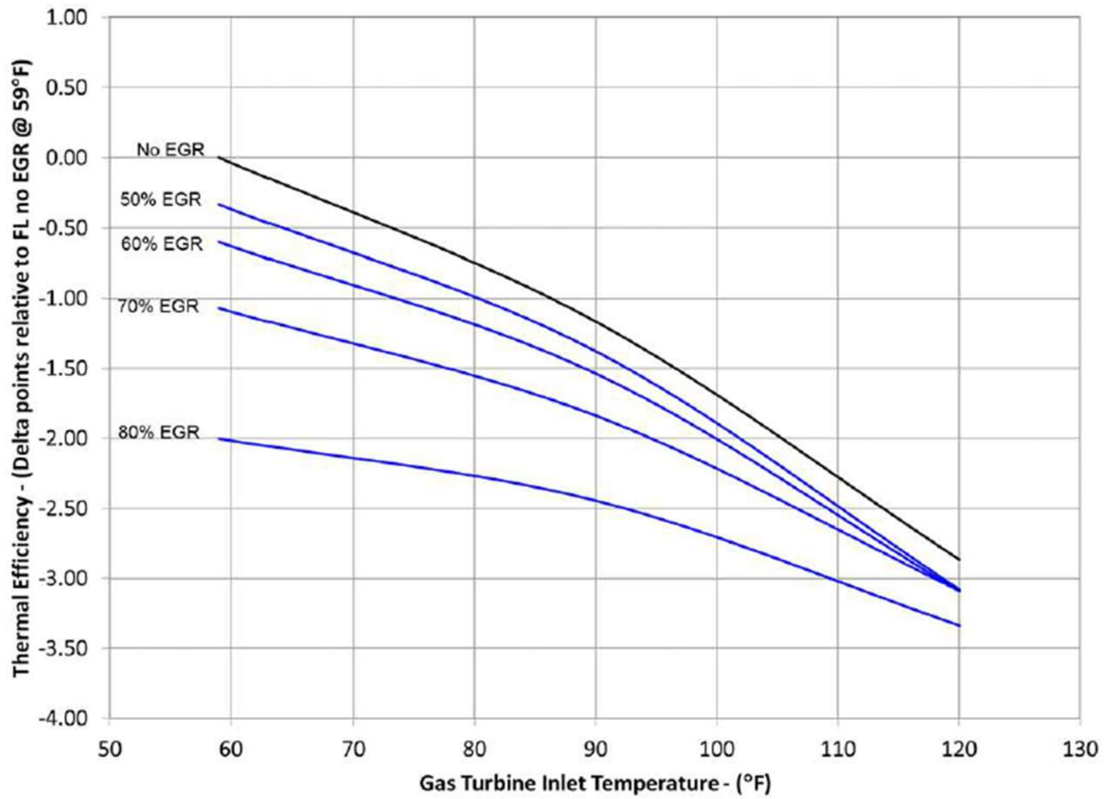

Figure 3. Full Load @ Constant EGR Levels – Thermal Efficiency vs Inlet Temperature

Parametric Analysis with EGR CED System Model

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- Full Load Analysis Results – Required supplemental O_2, CO_2 in exhaust flow

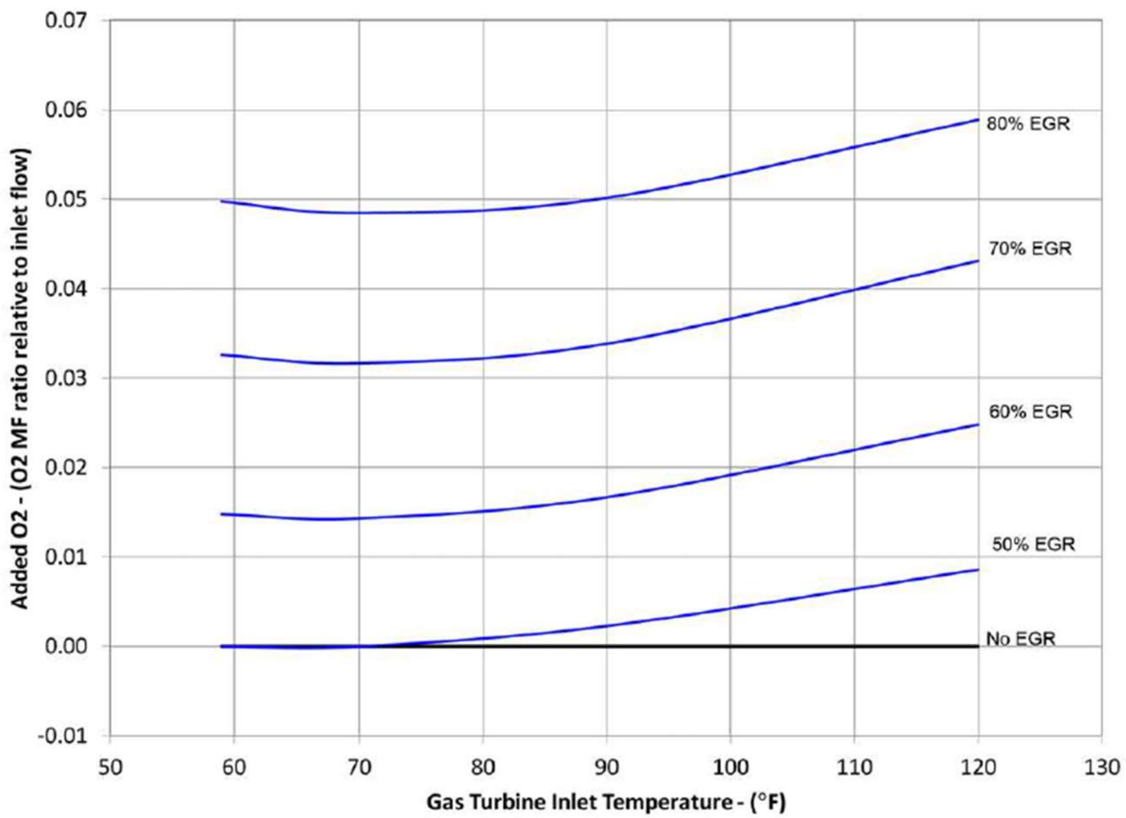

Figure 4. Full Load @ Constant EGR Levels – Added O2 at the GT Inlet vs Inlet Temperature

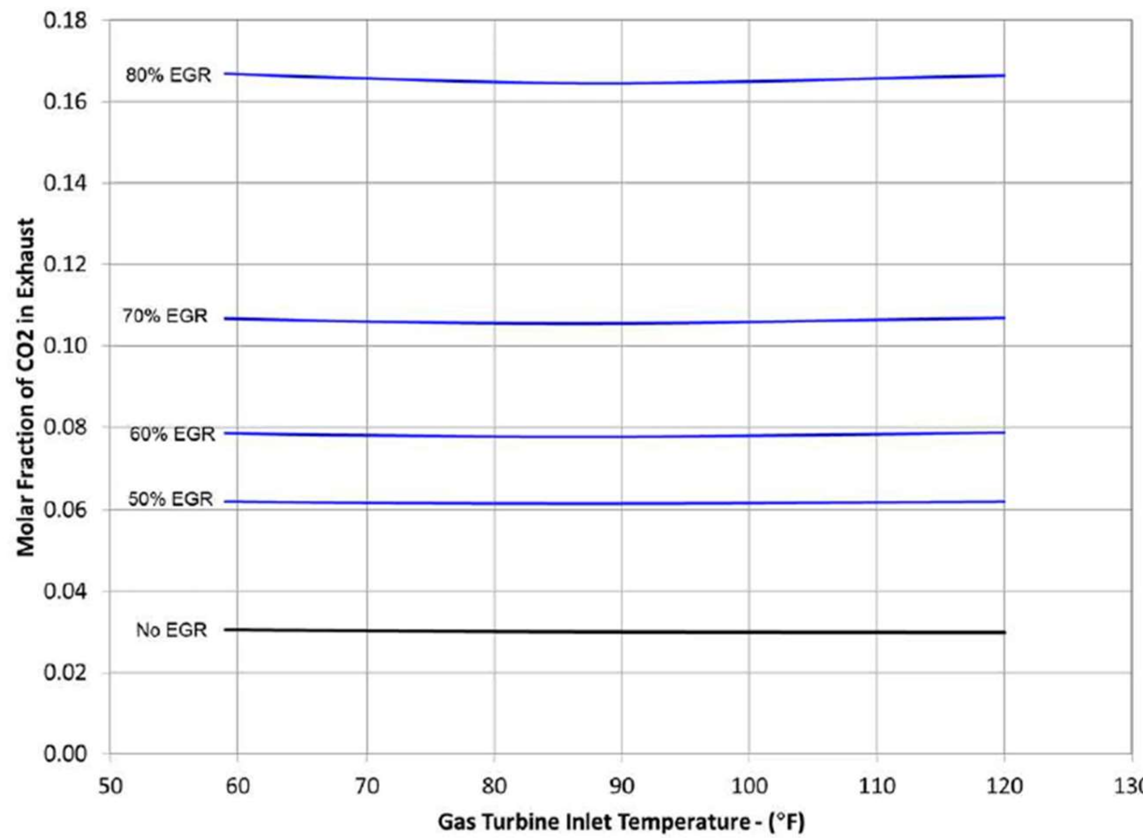

Figure 7. Full Load @ Constant EGR Levels – MF CO2 in Exhaust vs Inlet Temperature

Effect of EGR on Exhaust Gas Constituents and Inlet Gas Properties

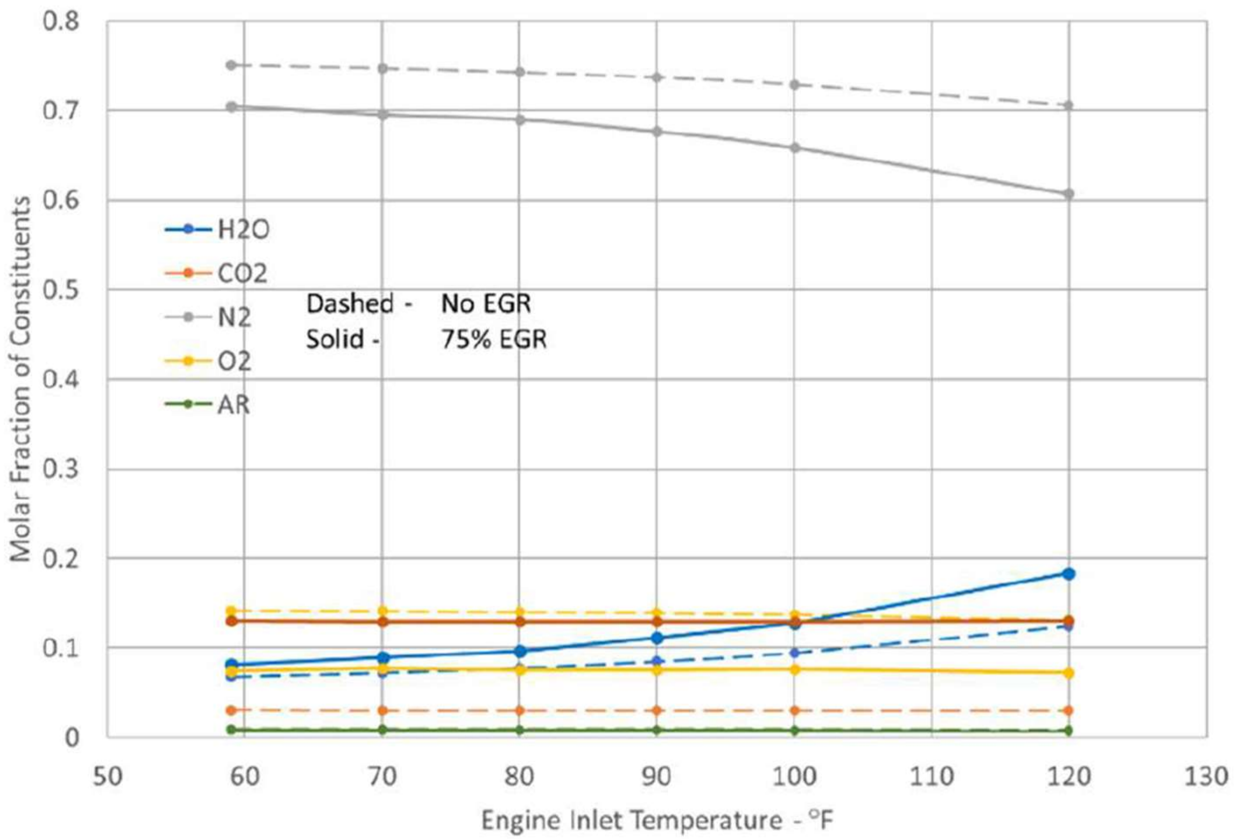

Figure 15. CED Exhaust Gas Constituents

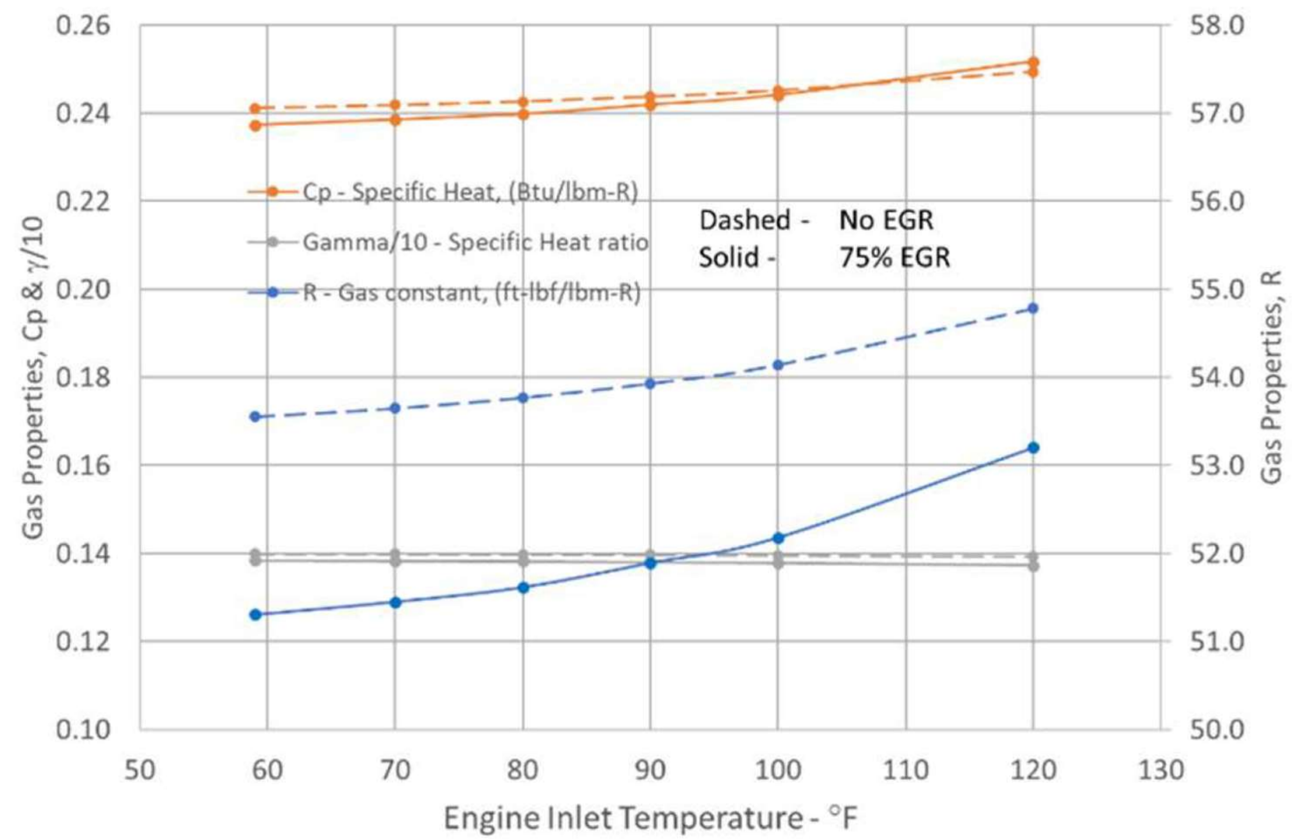

Figure 16. CED Engine Inlet Gas Properties

Parametric Analysis with EGR System Model

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- Compressor non-dimensional characteristics drive performance behavior
- Higher CO_2, more mass flow through the engine

Flow

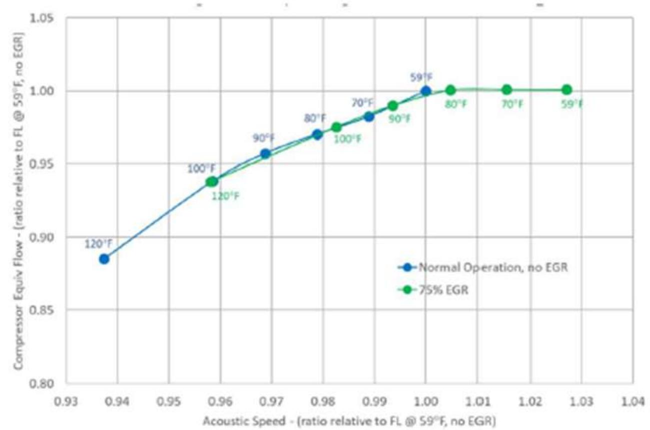

Figure 10. CED Compressor Characteristics – W_{eq} vs N_{ac}

Flow

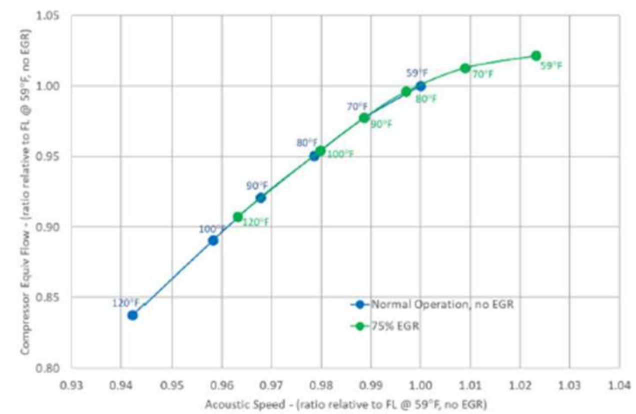

Figure 13. HED Compressor Characteristics – W_{eq} vs N_{ac}

CED

HED

Eff

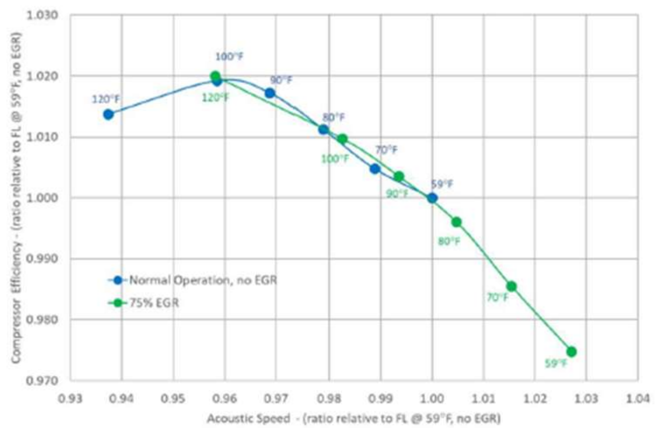

Figure 12. CED Compressor Characteristics – Eff vs N_{ac}

Eff

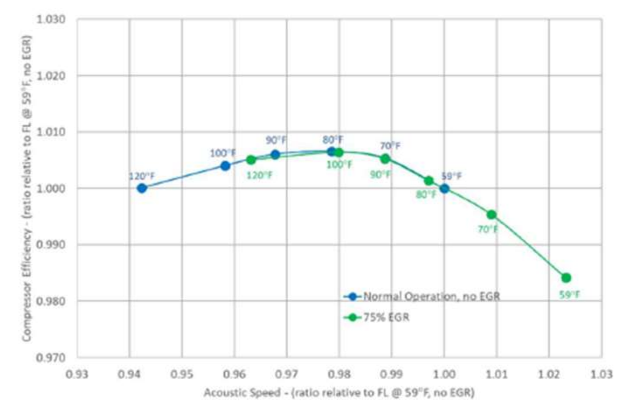

Figure 14. HED Compressor Characteristics – Eff vs N_{ac}

Combustion Behavior with EGR System

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- Chemical reactor network model of combustion system

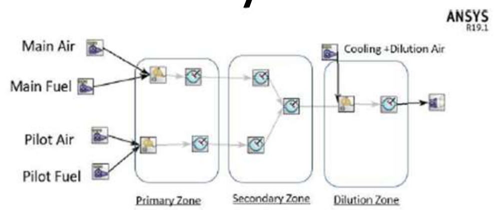

Figure 18. Chemical reactor network of a DLE gas turbine combustion system

  - Analysis of emissions, behavior with reduced O_2 (blow out), and noting laminar flame speed and change in equivalence ratio
  - O_2 mole fraction in the range of 14% and 16% is suitable from the emissions and flame stability point of view
  - There is a potential to reduce NOx emissions using EGR running with reduced O_2. CO will still be negligible.

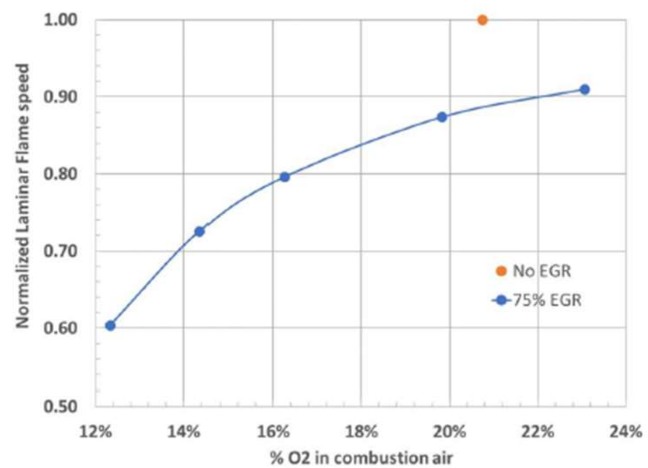

Figure 20. Ratio of predicted laminar flame speeds of the fuel-air mixtures to its value at no EGR condition

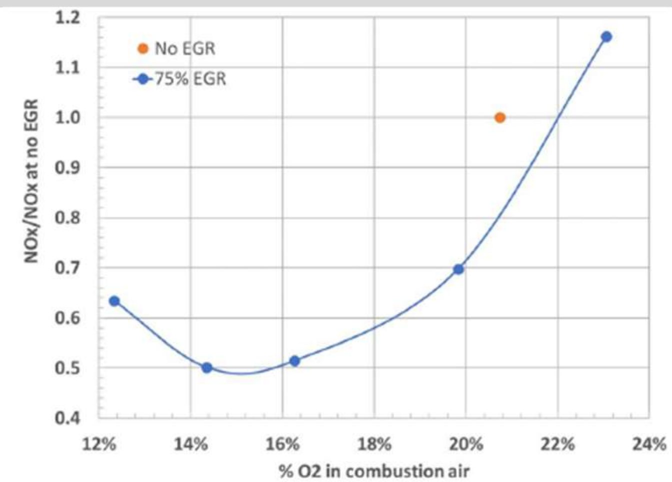

Figure 19. Ratio of corrected (15% O_2, dry) actual NOx to NOx at no EGR

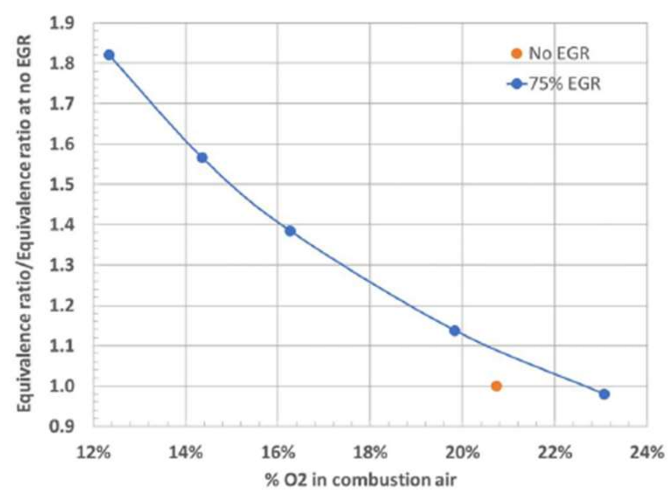

Figure 17. Ratio of actual equivalence ratio to equivalence ratio at no EGR for different level of O_2 in the combustion air

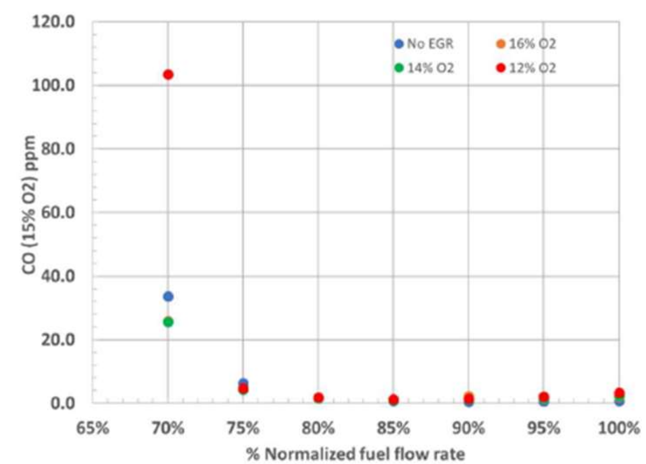

Figure 21. CO (15% O2, ppm) emissions relative to its no EGR value at 100% fuel flow versus reduction in fuel in the fuel-air mixture at full-load condition

Conclusions and Final Thoughts

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- Eliminating CO_2 emissions from gas turbine engines is highly desirable due to environmental and especially economic consequences
- Study concludes it is feasible to operate single or two shaft industrial gas turbine engines with significant amount of EGR, though requiring supplemental O_2
  - More O_2 addition is needed with higher EGR levels to sustain robust combustion
  - Gas turbines have about 3% molar fraction (MF) (4.7% mass fraction) of CO_2 concentration in the exhaust
  - For improved CC costs the target would be to increase the CO_2 concentration in the exhaust to at least 6% molar fraction
  - At 50% EGR, the gas turbine may not need supplemental O_2

Conclusions and Final Thoughts (cont)

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- Power will increase substantially with higher levels of EGR
- EGR increases the CO_2 concentration in the exhaust and reduces the exhaust flow. The Gas Cleanup System (GCS), scales inversely with this increased concentration.
  - Reduces the size of the capture system
  - Reduces power required to operate the capture system
  - Reduces number of stages or number of trains of capture system skids