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2022 Combined Heat and Power/District Energy System Portfolio Meeting
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Ultra-Efficient CHP with High Power/Heat Ratio using a Novel Argon Power Cycle

Miguel Sierra Aznar, PhD.
Chief Executive Officer

Decarbonizing Energy in 2 acts

1. Energy Supply Decarbonization

Accelerated Renewables deployment
True decarbonization requires our primary energy to come 100% from renewables, growing at a pace that matches energy demand growth and prevent new fossil.

Eliminate Firm-Capacity's carbon footprint
*Implementation of **CCS** technologies is key to preventing the lock-in of CO_2 emissions while maintaining the dispatchable and reliable operation of the power grid.*

CO_2

Buildout Energy Storage infrastructure
*Short-, medium- and long-term energy storage in the form of batteries and **hydrogen** among other forms enables the grid in surmounting intermittency and supply-demand time disparity*

H_2 Li^{+1}

Buildout Synthetic Fuel generation infrastructure
Generate alternatives energy vectors such as **H_2** and **NH_3** to power hard to electrify sectors such as heavy transport and heavy industrial.

H_2

2. Energy Demand Electrification

Buildout of electrical transmission & distribution
Expand high- and medium-voltage transmission connecting renewable resources with consumers and enabling efficient interstate electricity trading.

Electrification of residential & commercial sectors
Both sectors already fulfill ~50% of their energy demand through electricity. Through the deployment of electric appliances distributed emission will be avoided.

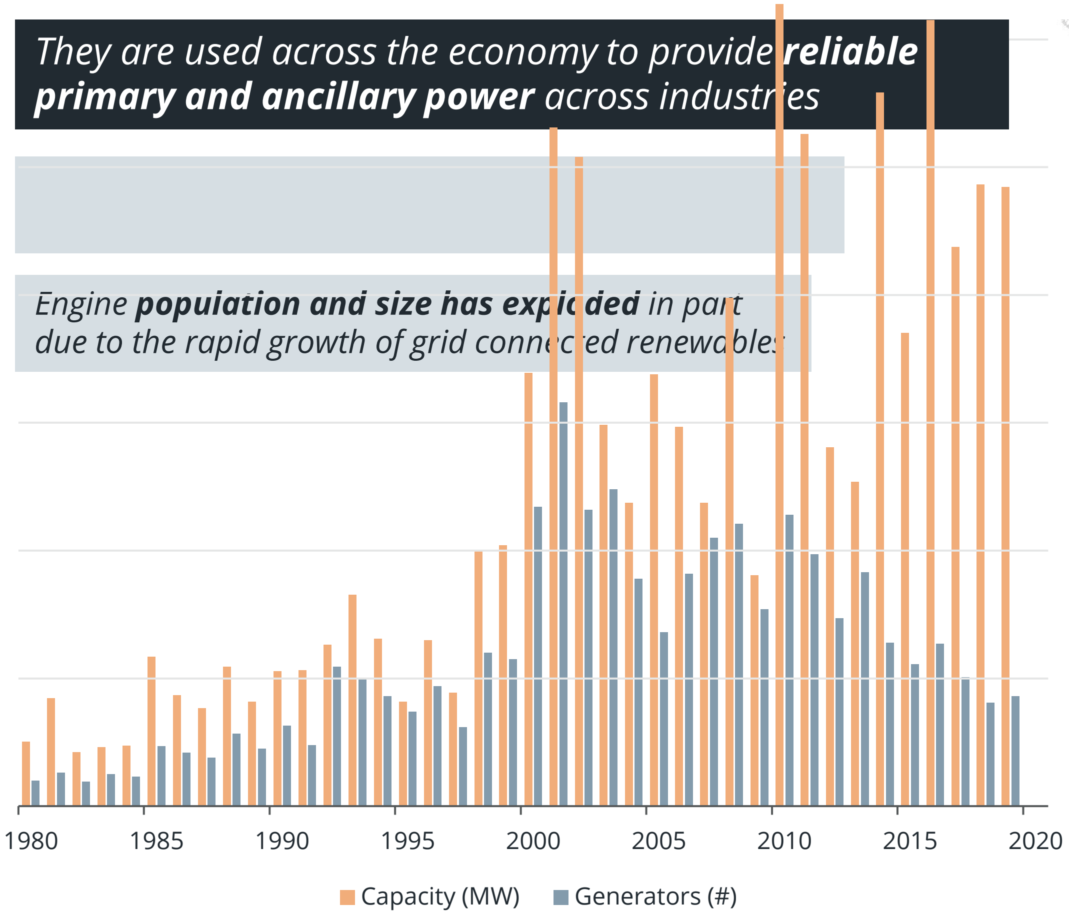
Electrification of transport and smart metering
Accelerate deployment of electric vehicles and associated charging infrastructure including smart grids with demand response capability.

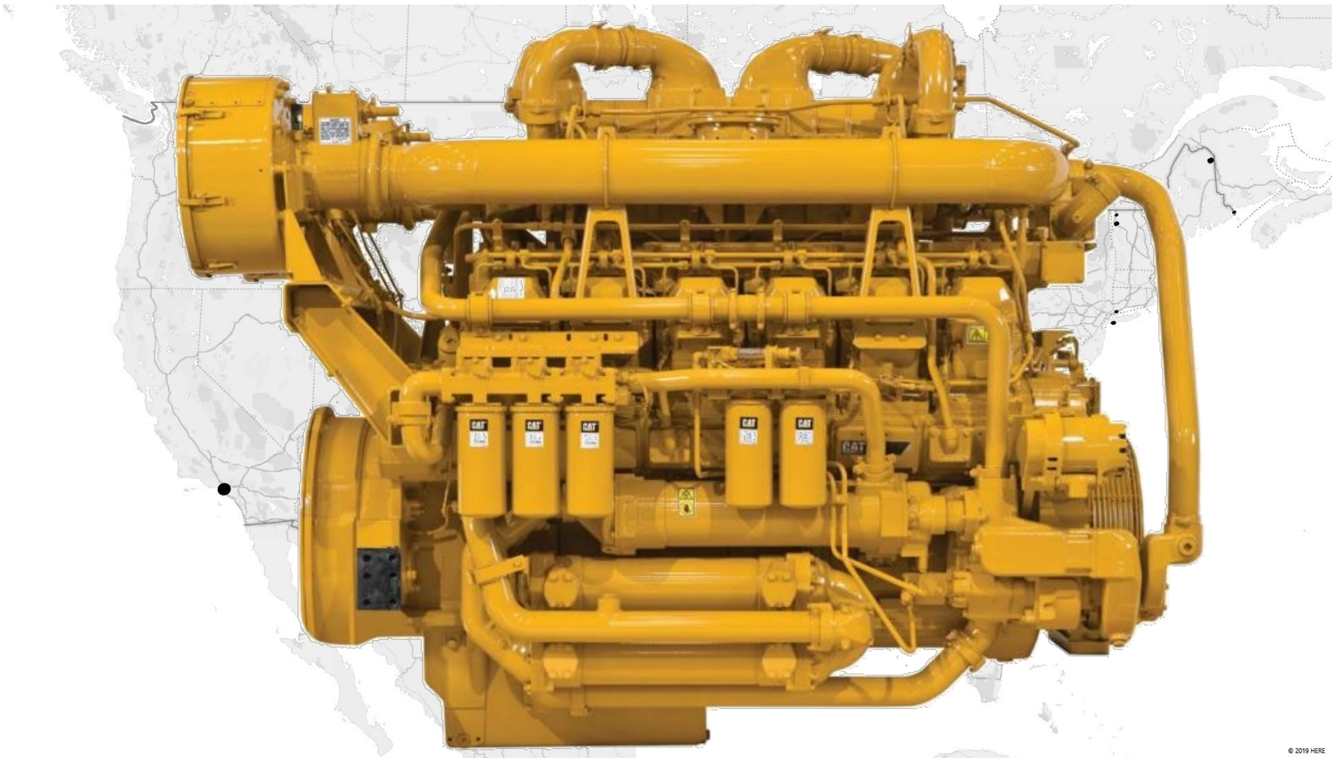
Deploy synthetic fuels for hard to electrify sectors
Adapt heavy transport and industry equipment to using green alternative fuels (e.g., H_2, NH_3) through new technology such as fuel cells, hydrogen furnaces, etc.

RECIPROCATING ENGINES CONTINUE TO BE THE WORKHORSES OF THE ECONOMY

They are used across the economy to provide ***reliable primary and ancillary power*** *across industries*

Engine ***population and size has exploded*** *in part due to the rapid growth of grid connected renewables*





They're responsible for more than ***70 million $MtCO_2$*** *emissions annually alongside air polluting emissions.*

Source: US EIA

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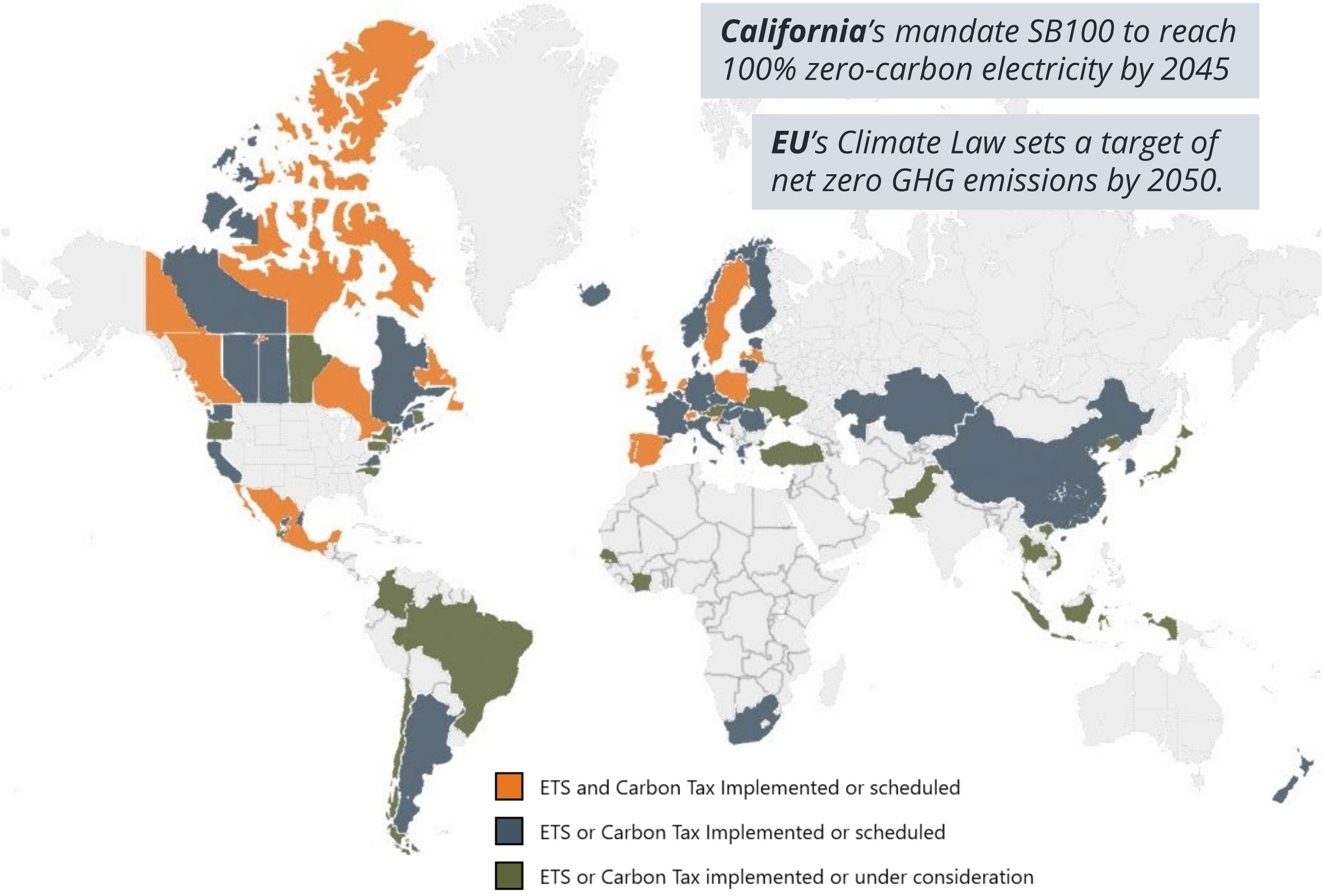
But the need to decarbonize is urgent

Countries and regions across the globe are launching combinations of national carbon markets and carbon taxes alongside regulations

***California**'s mandate SB100 to reach 100% zero-carbon electricity by 2045*

***EU**'s Climate Law sets a target of net zero GHG emissions by 2050.*

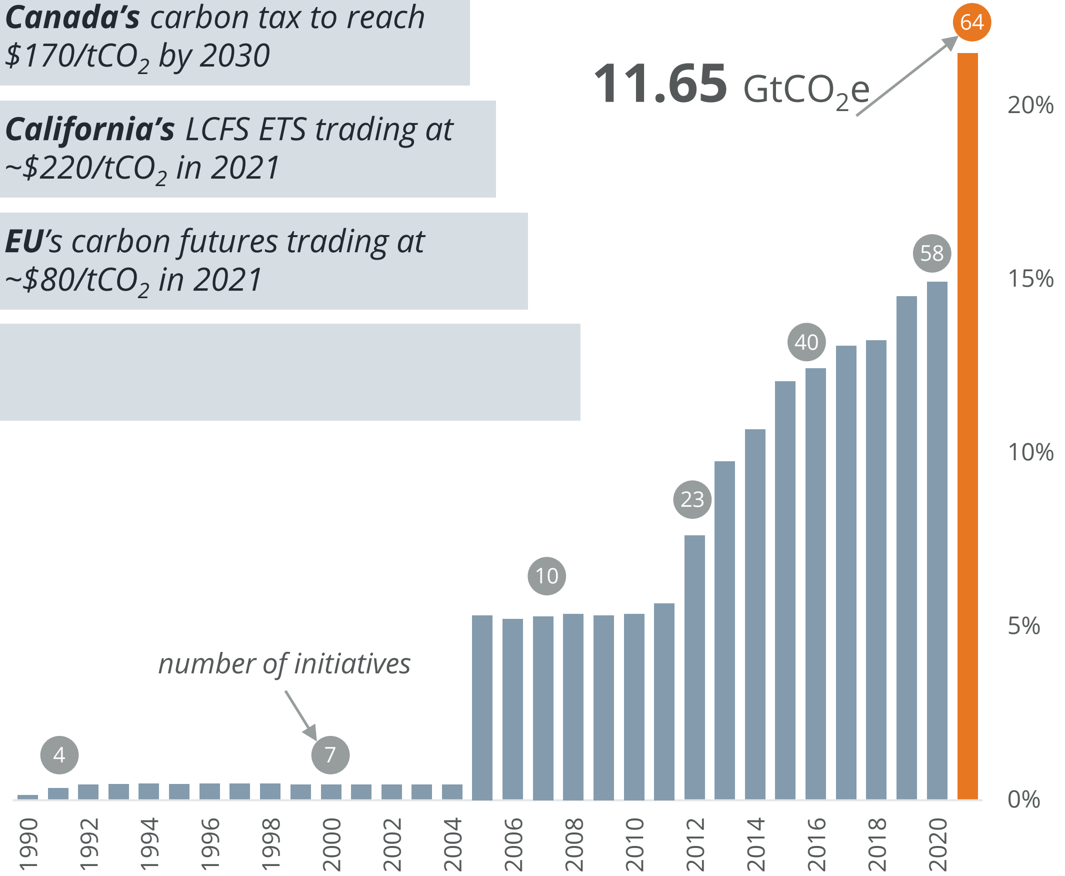


Share of global greenhouse gas emissions covered by carbon pricing policies continue to increase rapidly

***Canada's** carbon tax to reach \$170/tCO_2 by 2030*

***California's** LCFS ETS trading at ~\$220/tCO_2 in 2021*

***EU**'s carbon futures trading at ~\$80/tCO_2 in 2021*



Source: World Bank. 2021; ICE 2021; CARB 2021; EU Commission

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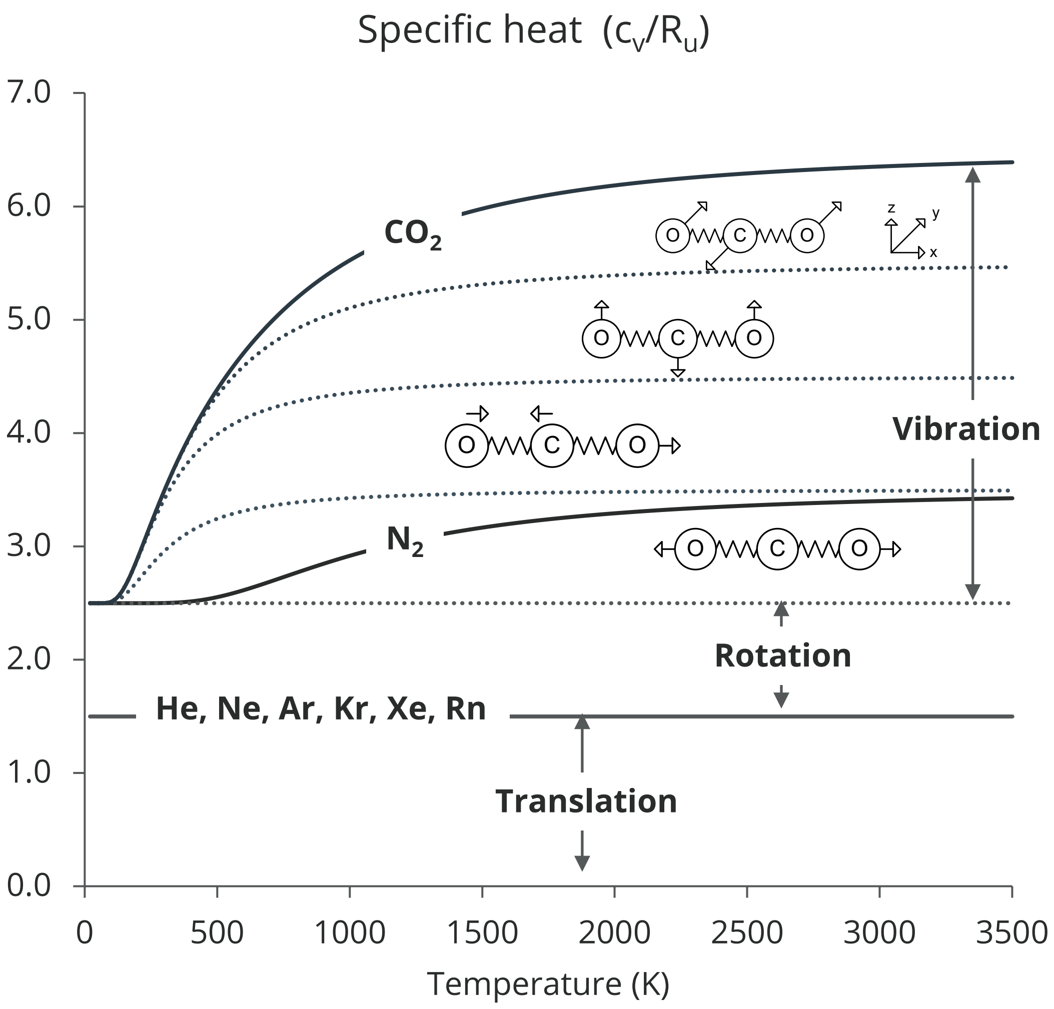
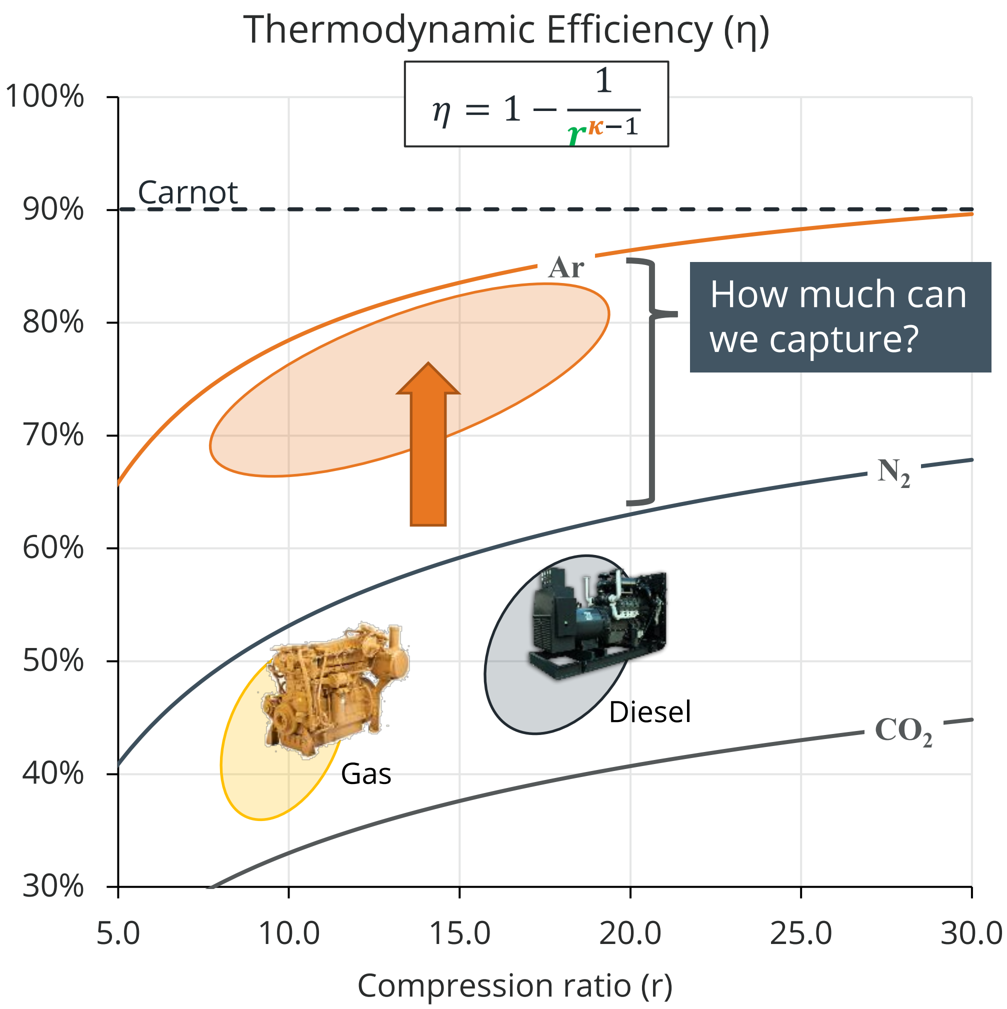
Argon Breathing Engines

PUSHING THE THERMODYNAMIC BOUNDARIES OF PERFORMANCE





But there are challenges… hard ones!

Argon rich working fluids result in **higher peak temperatures** and **pressures** than air…

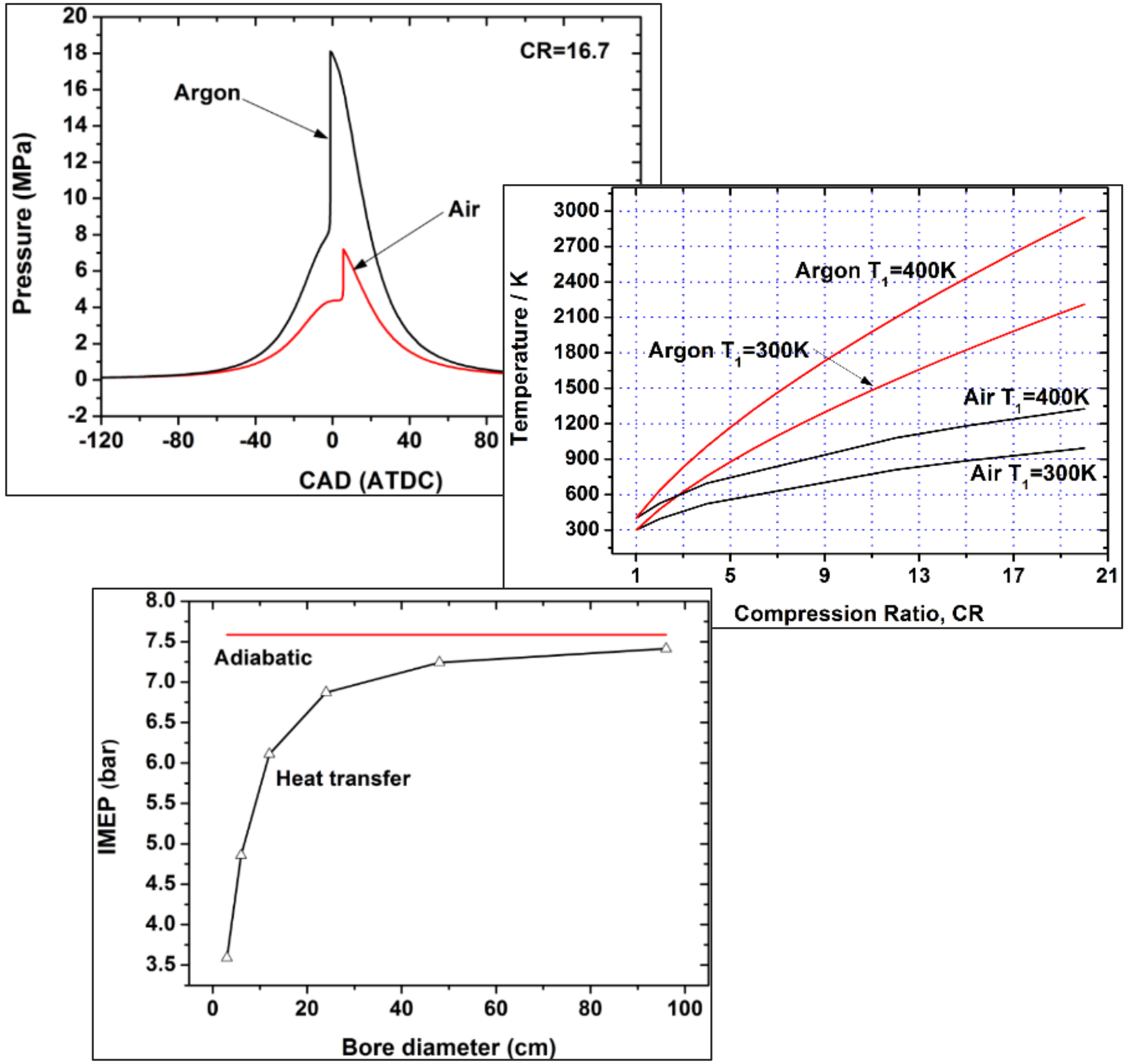
which, for reciprocating engines, it means:

1. Potential for higher **heat losses**
2. Higher propensity to **knock**
3. Smaller window of reliable combustion and thus narrower **operation range**.

BUT large bore engines **approach adiabatic**, scaling with their surface to volume ratio (1/B)

compounded with the **lower heat transfer** quality of Argon

makes large RICE **less sensitive** to higher in-cylinder temperatures.

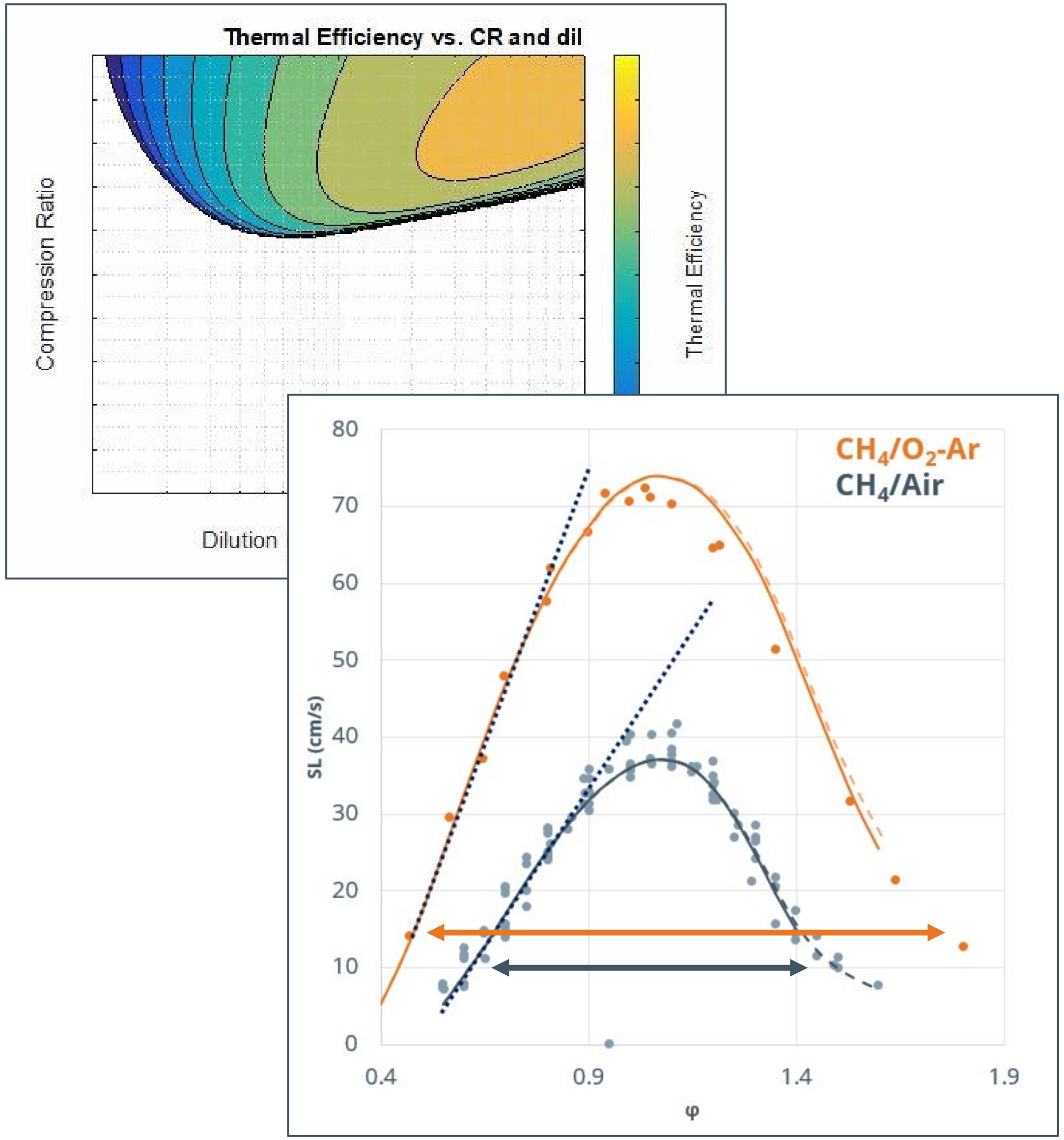


PRELIMINARY KNOCK AND FEASIBLE OPERATION

Solving the challenge of Knock and operational range needs **additional tunning** and use of all degrees of freedom at our disposal.

1. Synthetic working fluids enable **fine control of charge composition** expanding control beyond that of injection and ignition timing.
2. Argon affords radically **higher flame speeds** at a **wider range** of equivalence ratios.
3. Particularly, the APC provides at a minimum **3 additional degrees of freedom** or control knobs.

Making use of the above, allows to **avoid knock regions** as well as **expanding the misfire limits**.



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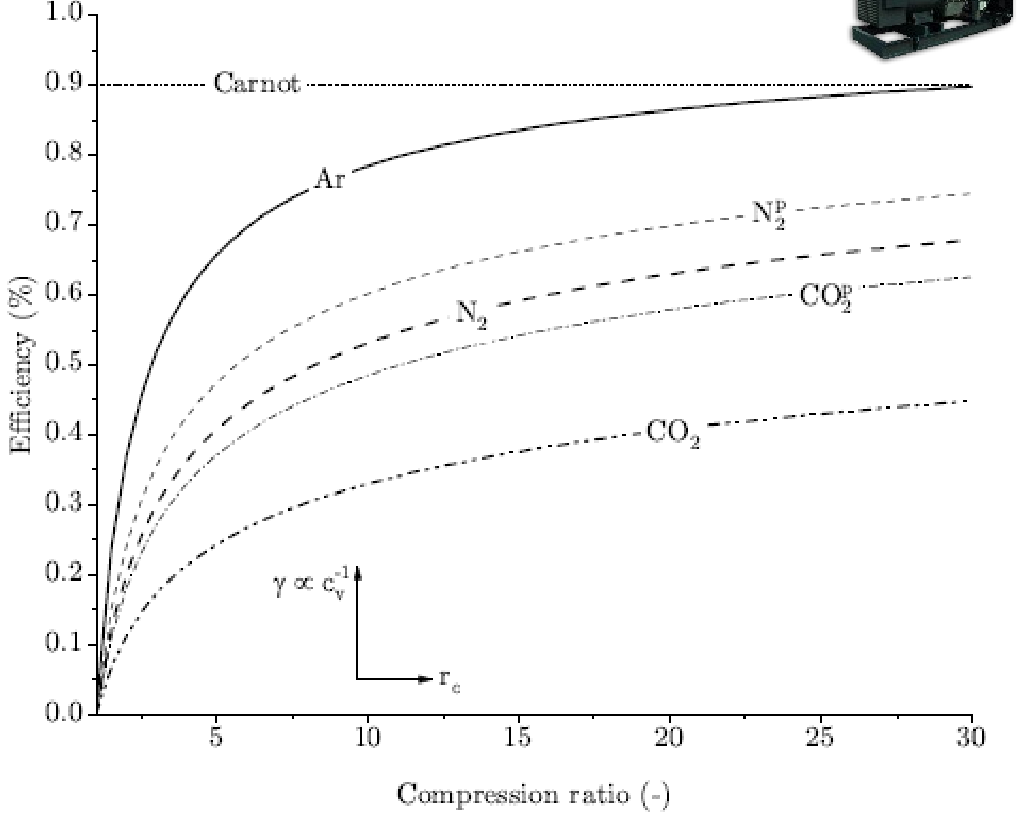
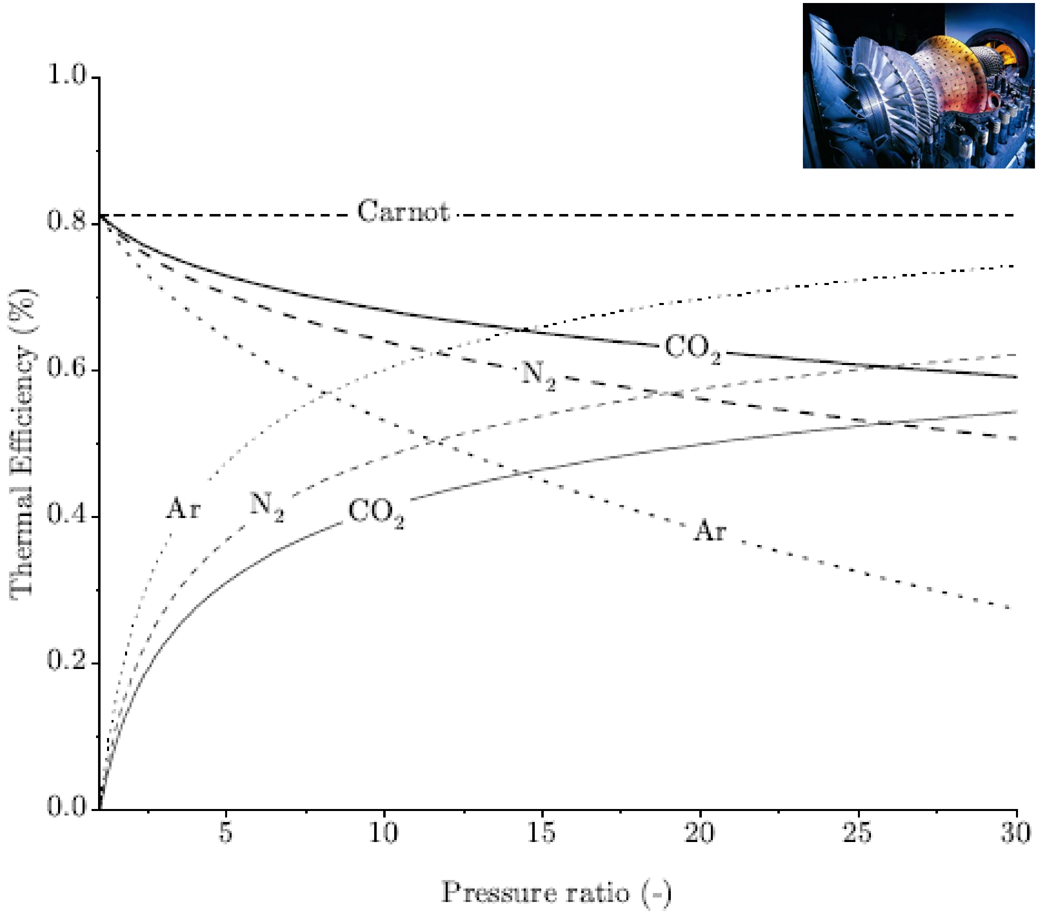
ARGON & SUPERCRITICAL CO_2 POWER CYCLES





The Argon Power Cycle

Making the APC Practical

A close-loop gas recirculated thermodynamic cycle delivering ultra-efficient, flexible, and zero emissions power.

Simple and versatile, intrinsically clean and agnostic to fuel source, retrofittable onto existing power generation assets.

1. Ultra-Efficient Power Generation

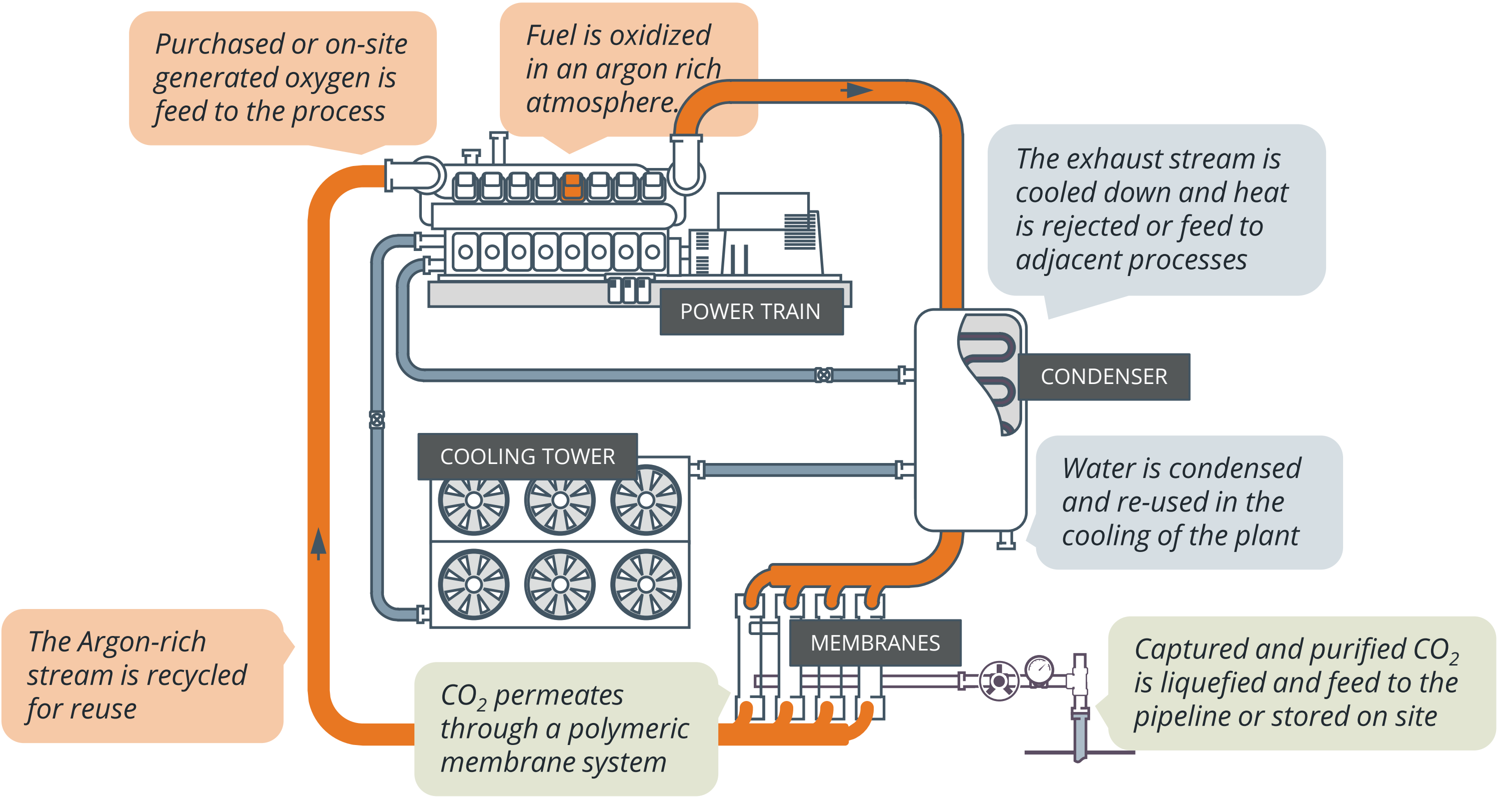
The use of a monoatomic gas as the working fluid radically increases the system conversion efficiency and **prevents** the formation of **harmful nitrogen oxides**.

2. Heat and Water Recovery

The recovery of water and heat **reduces** the **water consumption** and improves overall plant efficiency.

3. Carbon Capture and Purification

Control over the recycled argon stream composition enables the **lowest cost carbon capture** and real-time, and efficient **Hydrogen blending**.



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Net Benefits of RICE + APC Plants

Hydrogen Mode

1. Fuel Cell competitive efficiency.
2. No constrained by NOx.
3. Low sensitivity to H_2 quality.
4. Lower cost components (pistons, etc.).
5. Low sensitivity to cycling compared to fuel Cells.

Plant Item	Efficiency Gain
Engine	(+) 18%
Air processing	(-) 0%
Gas processing	(-) 0%
Fuel compression	(-) 1-2%
Net change	**(+) 15%**

Natural Gas Mode

1. Higher efficiency than conventional air breathing cycles.
2. 100% CO_2 Capture with not air pollutants.

*Builds on the the flexible characteristics of RICE.

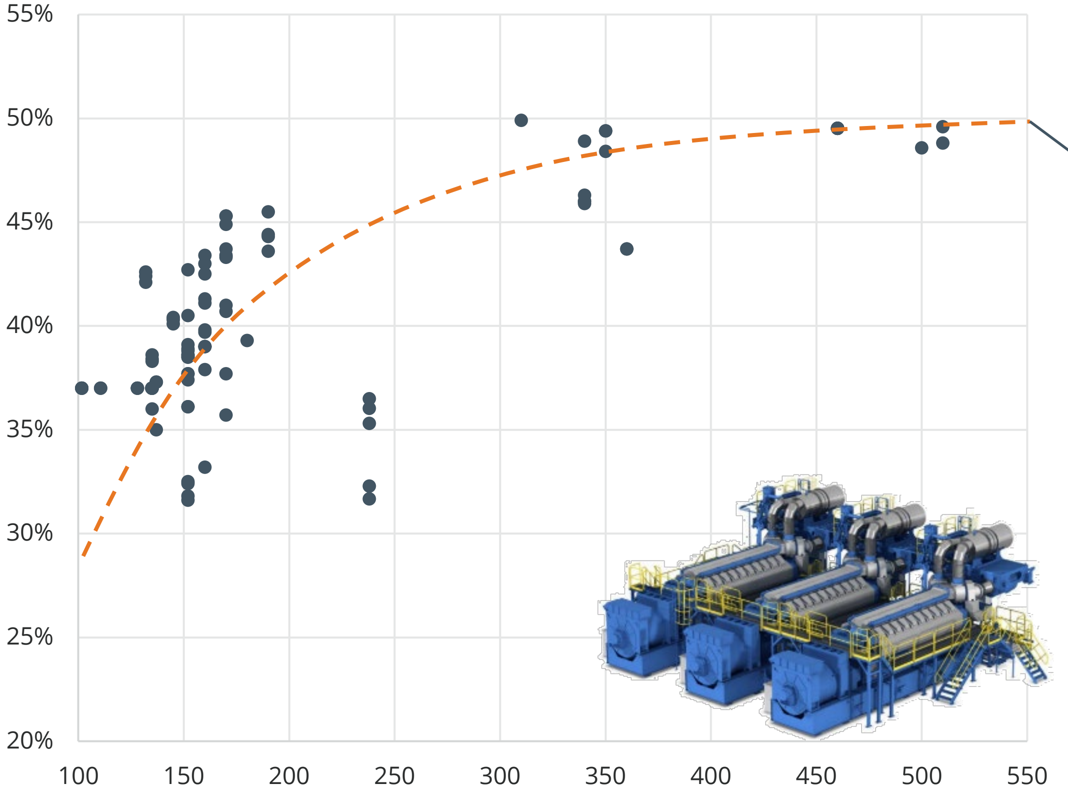
Plant Item	Efficiency Gain
Engine	(+) 18%
Air processing	(-) 5-7%
Gas processing	(-) 2-3%
Fuel compression	(-) 1-2%
Net change	**(+) 5-10%**

What is the potential impact?

Engine OEMs have done a commendable job in reaching **near theoretical performance** limits through R&D.

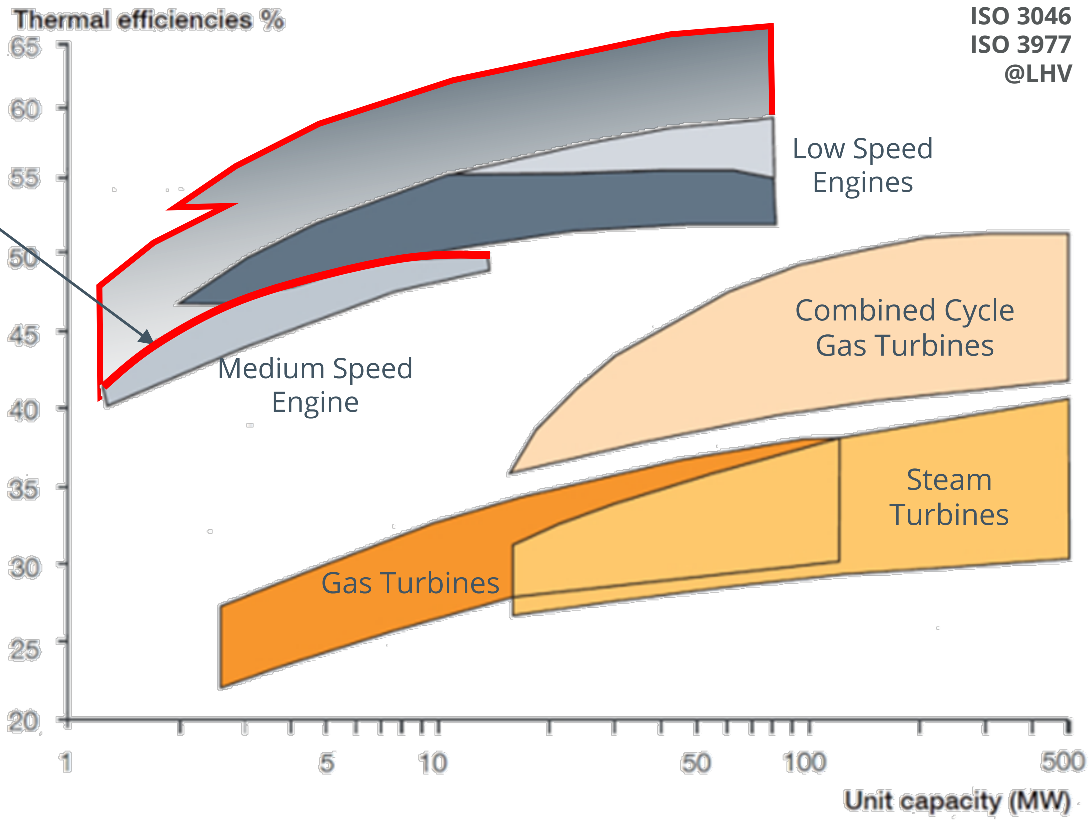
The APC provides a path to **improved performance** and **eliminate emissions** while leveraging decades of RICE R&D

Off-the-shelf NG RICE Efficiency



Source: Engine OEM Spec Sheets.

Thermal Efficiency Comparison



Source: MAN Diesel & Turbo

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

ADVANCED MANUFACTURING OFFICE

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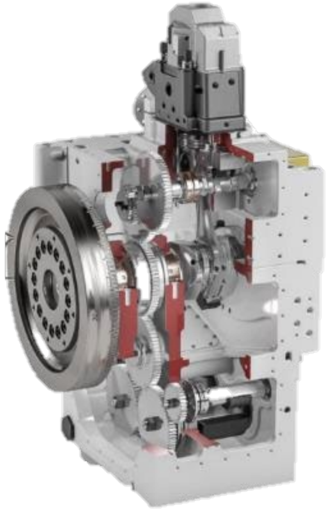
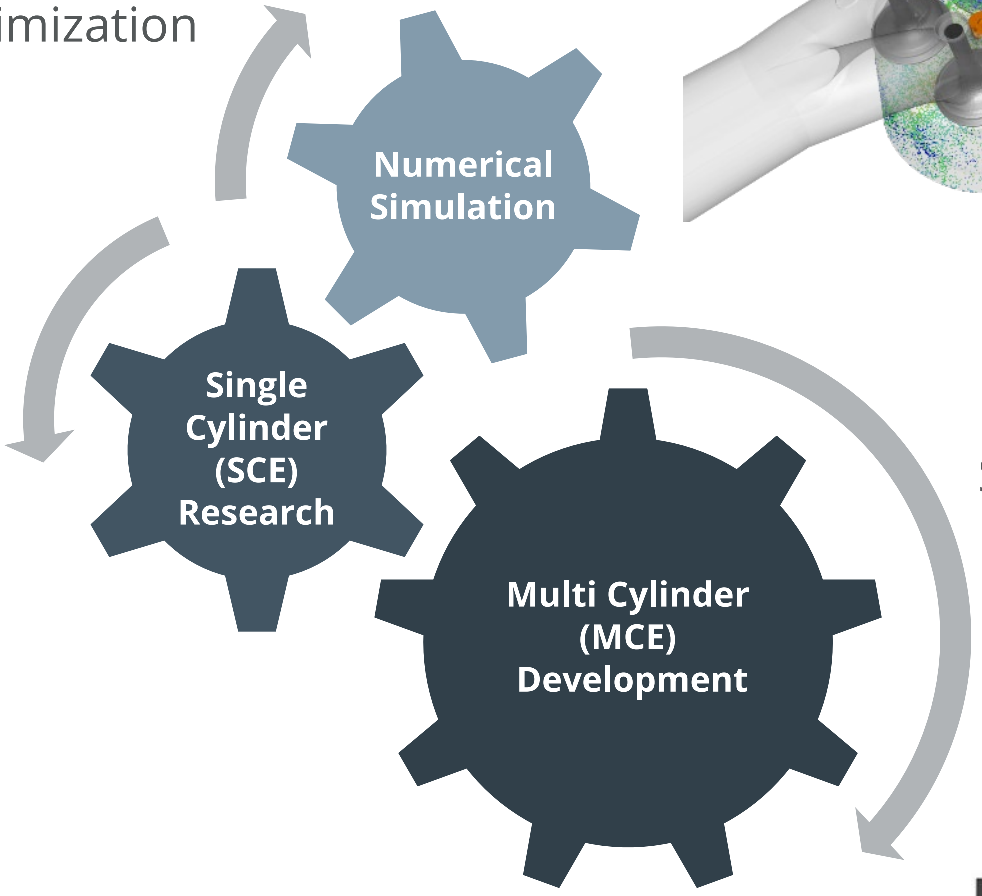
PROJECT R&D APPROACH

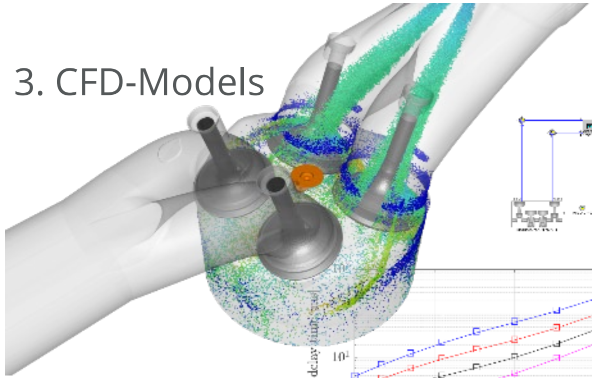
Numerical Modelling and System Optimization

Experimental validation and optimization

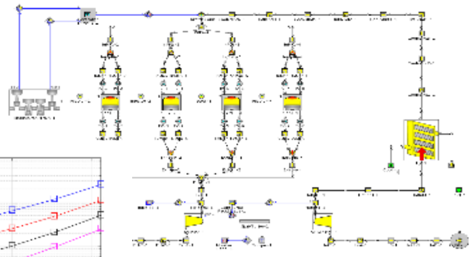


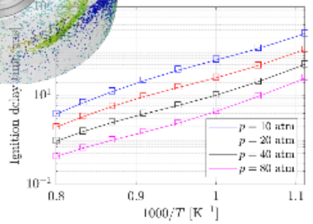


3. CFD-Models



2. Process Models





1. Chem. Kinetics Models

Simulation and SCE results to inform MCE operation and optimization

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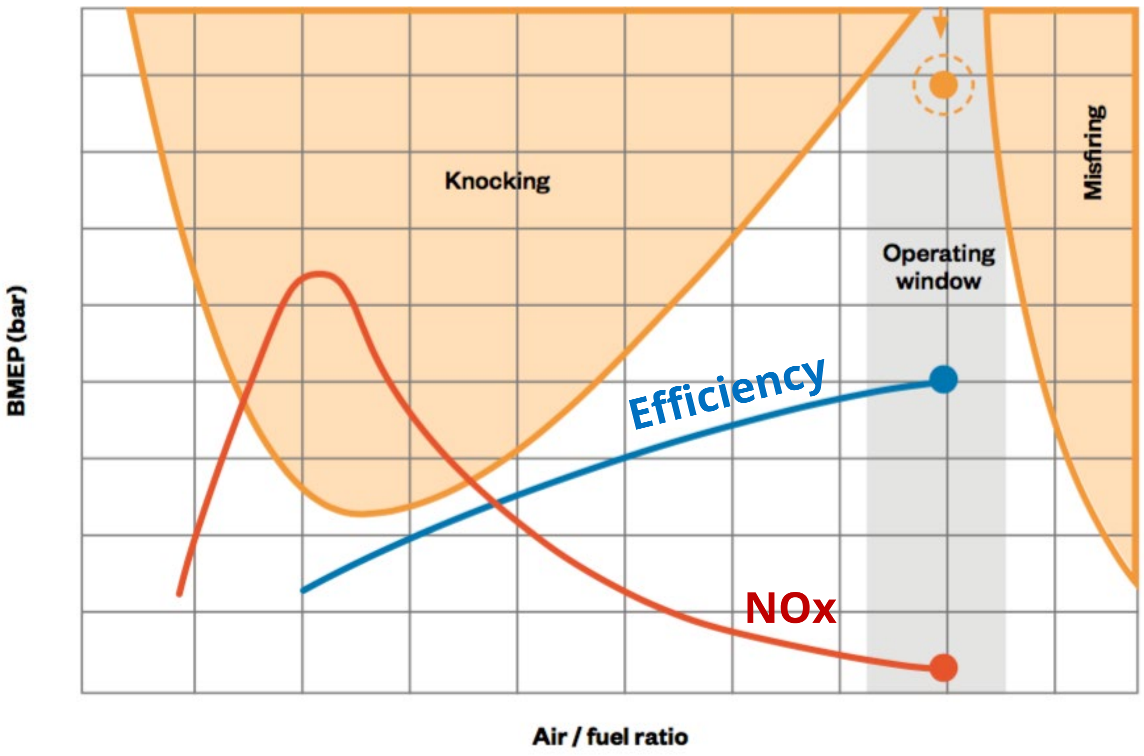
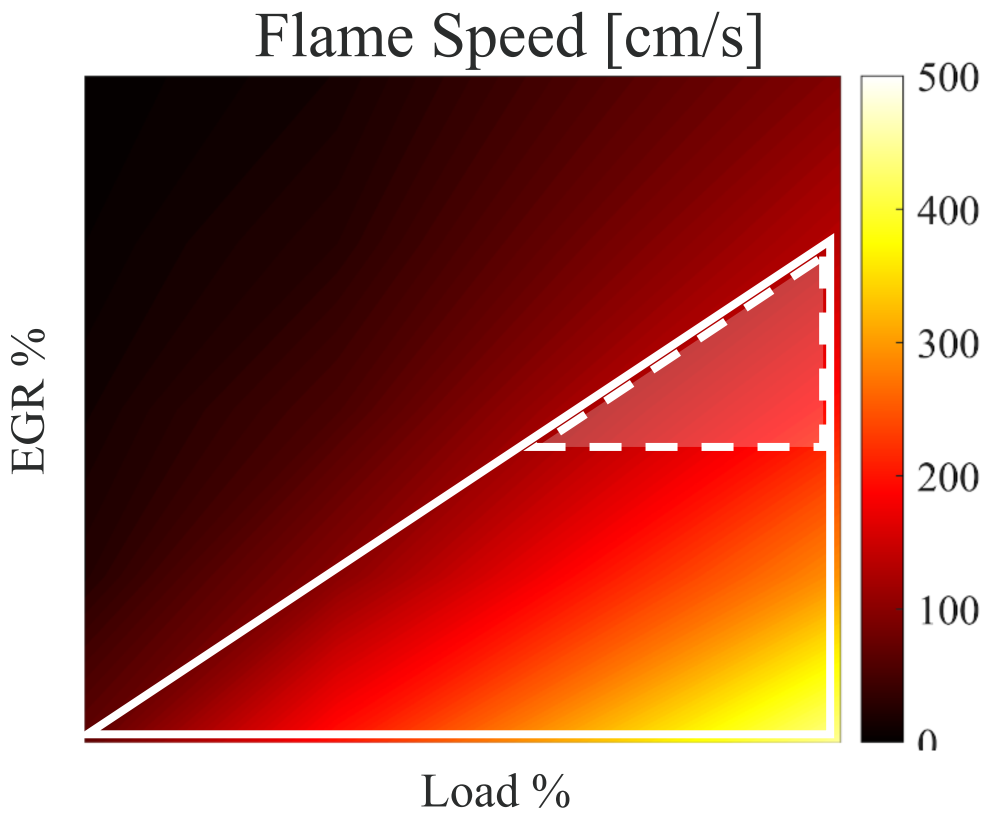
Engine Feasible Operational Region

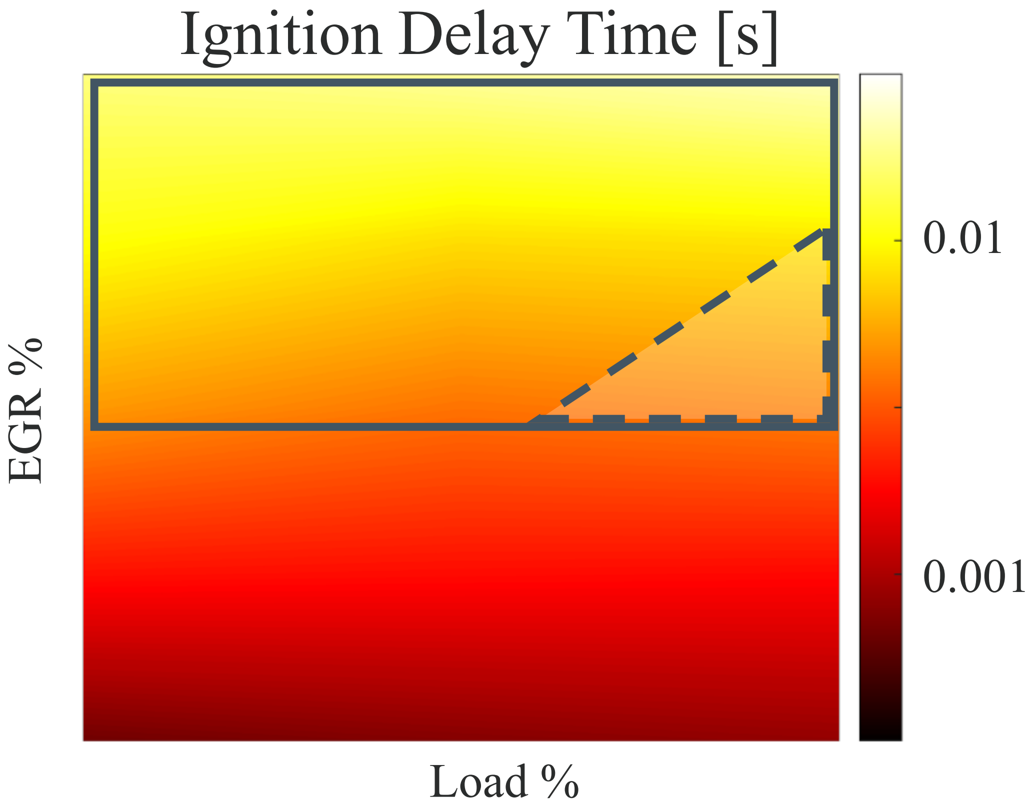
- Conventional air breathing engines navigate a complex space, balancing **combustion stability**, **reliability** and **emissions** to deliver highest efficiency and power density
- Argon breathing engines are **not constrained by emissions** and thus expand the realm of feasible operating points for which performance can be optimized.
- Nonetheless, knocking regions are greater in size pushing operation window towards the misfiring region.
- In navigating around the Knock region, the APC provides **additional routes** to optimize for performance across the load range.

Conventional RICE Operational Range

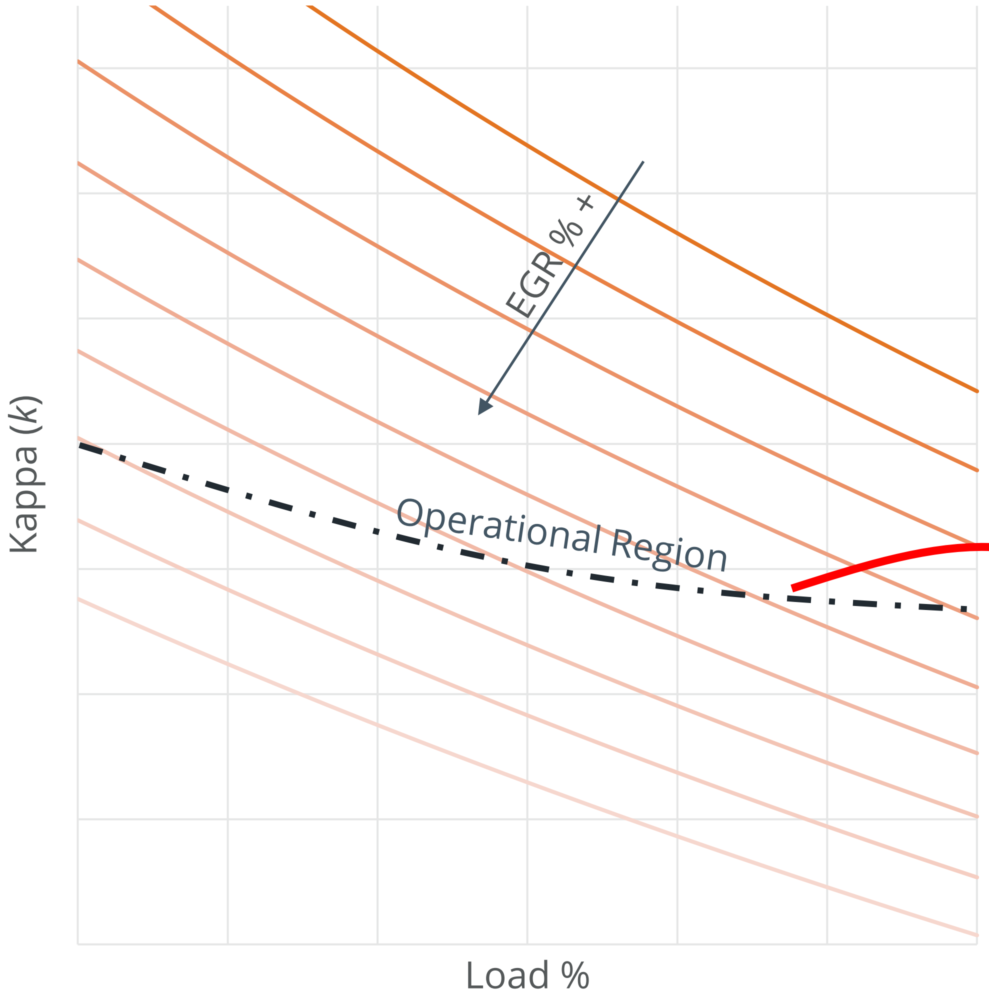


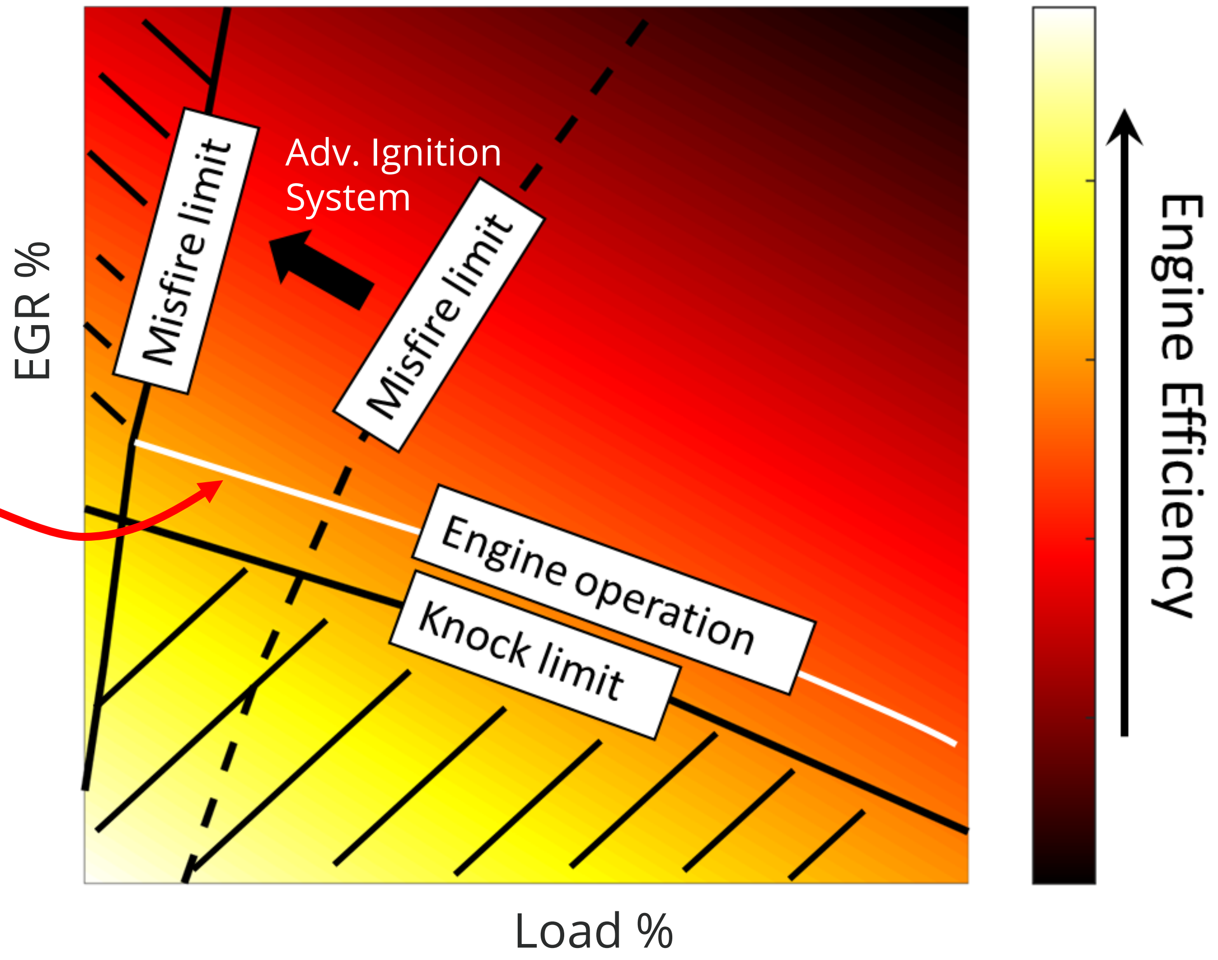
DEFINING APC OPERATIONAL RANGE





Maintaining Performance Across the Load Range





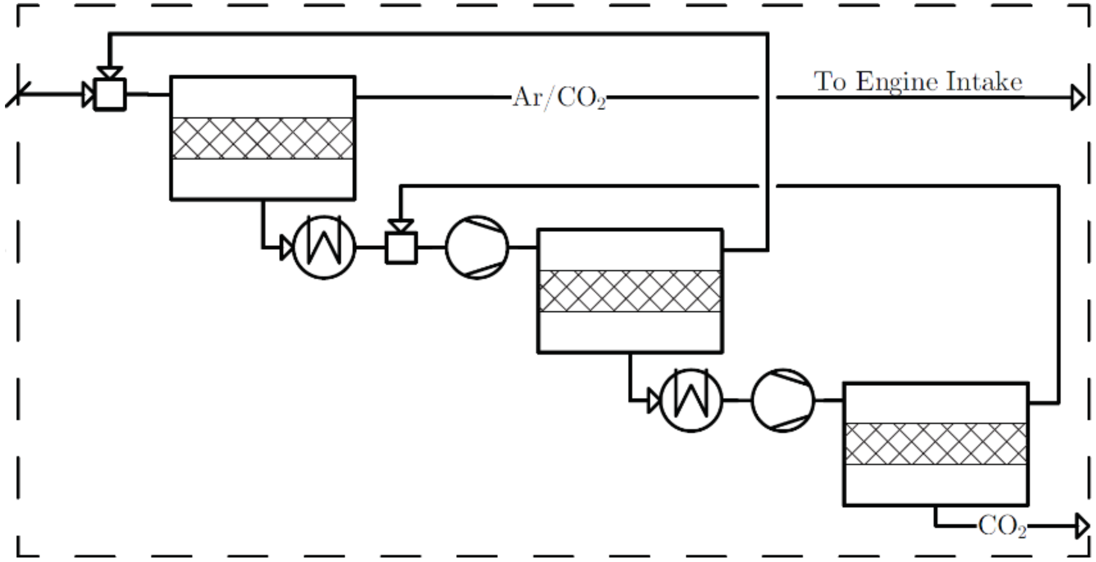
CO_2 SEPARATION - COST AND CHARACTERISTICS

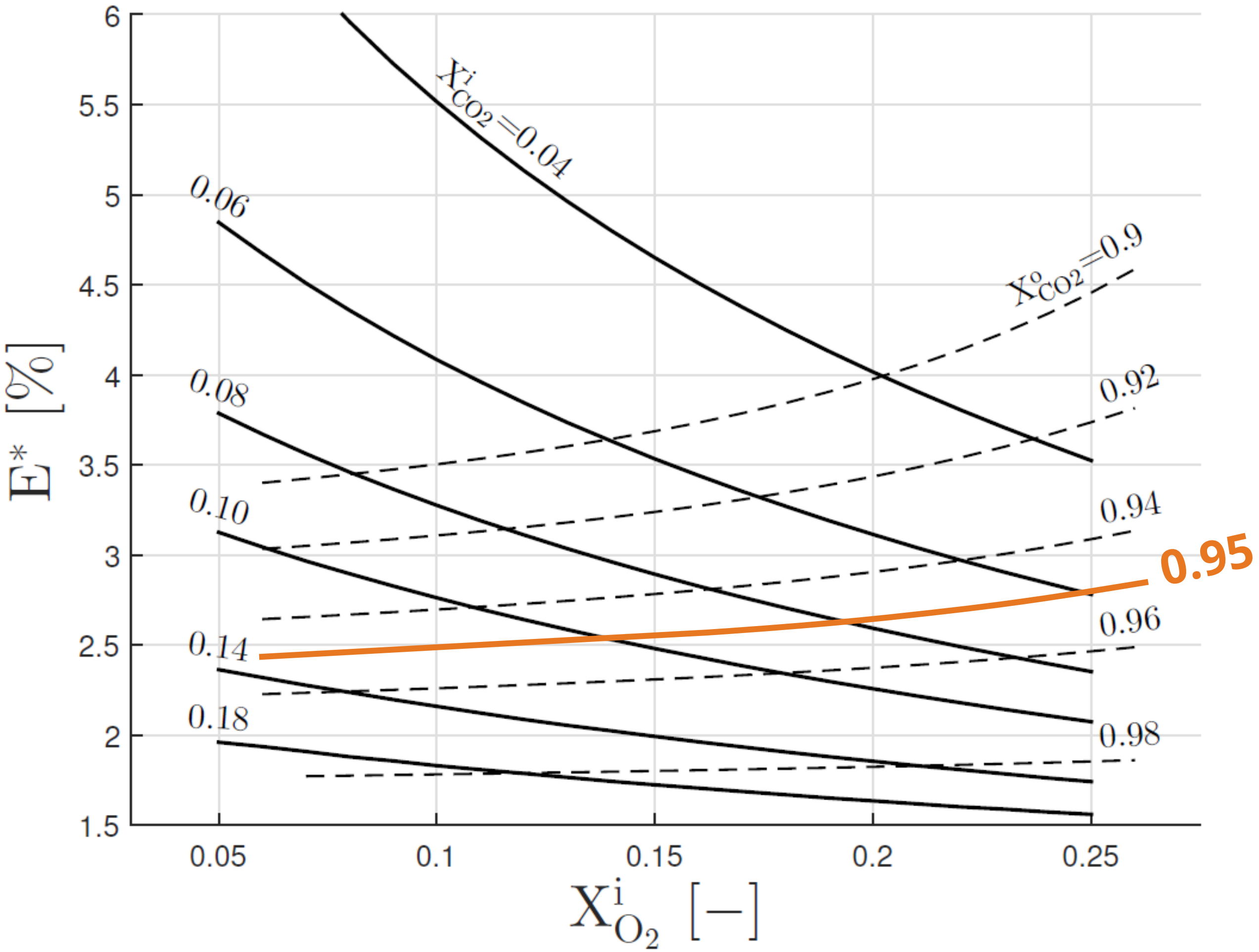
Membrane separation is ideal in close loop configurations:

1. They conform to a **continuous plug-flow** reactor model.
2. The add **no consumable** to the process.
3. No need capture all CO_2 in a single pass.
4. Easy to operate, maintain and cheaper than amine system under the right operating conditions.
5. No complex chemistry involved

Image: MTR, Inc.

CO_2 SEPARATION – PERFORMANCE

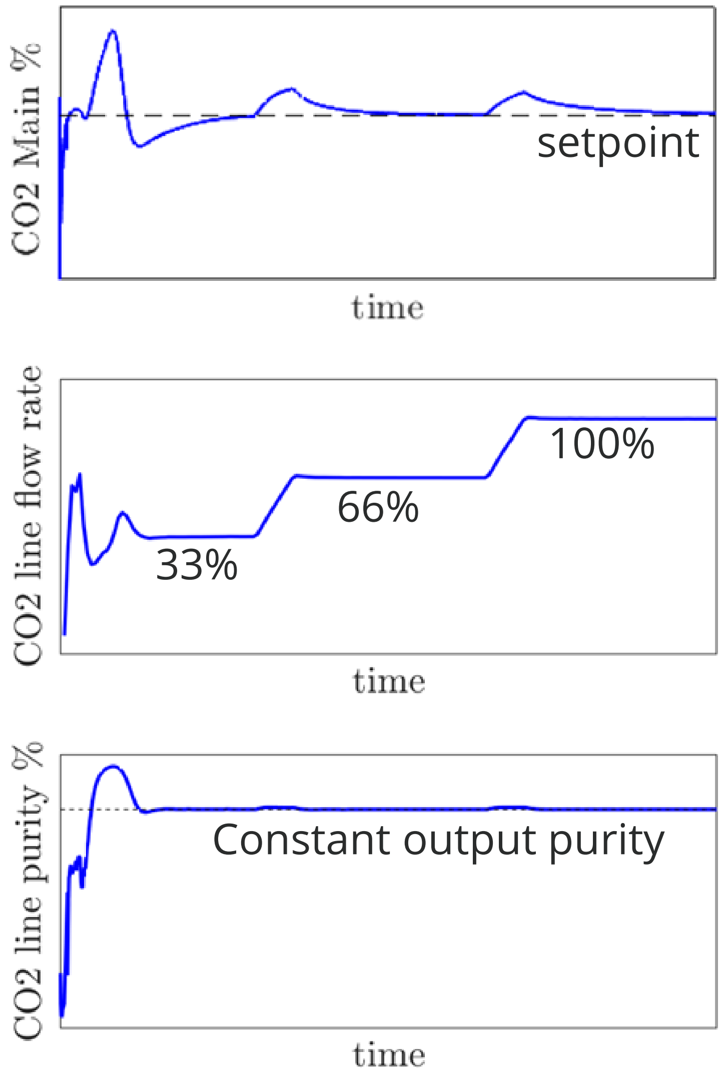




CO_2 SEPARATION – CONTROL

Membrane system properly controlled provides a great amount of benefit regarding expanding the operational range of the APC.

- Through **active management of the system pressures** the amount and purity of the CO2 can be tuned within a wide range.
- The membrane separation system **affords fine control** over the composition of the recirculating stream.
- Additionally, membranes act as **controllable buffers** between engine exhaust and intake conditions.
- All together, membranes not only serve to capture CO2 but as a **means to expand the feasible operational range** and optimize the performance of the argon breathing engine.



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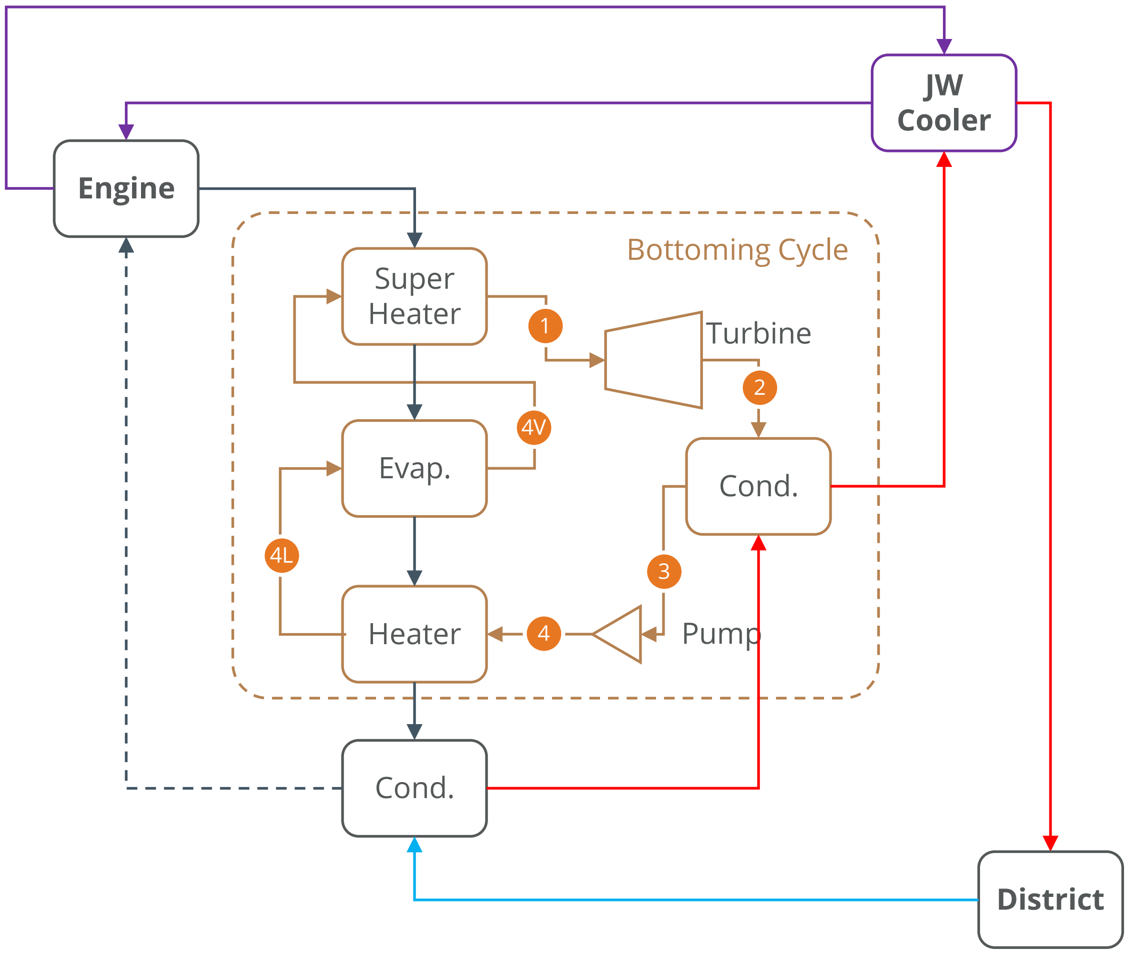
Two Distinct Bottoming Cycle Cases

- As the **efficiency of the engine is increased** through the implementation of the APC, exhaust temperatures drop.
- Additionally, as the **engine bore size increases**, the heat losses to the cooling jacket decrease slightly balancing the quality of the exhaust heat.

	Case 1	Case 2
Scale	<5MW	>5MW
Efficiency	30-40%	40-50%
Exhaust Temp	>350 °C	<350 °C

General System Diagram

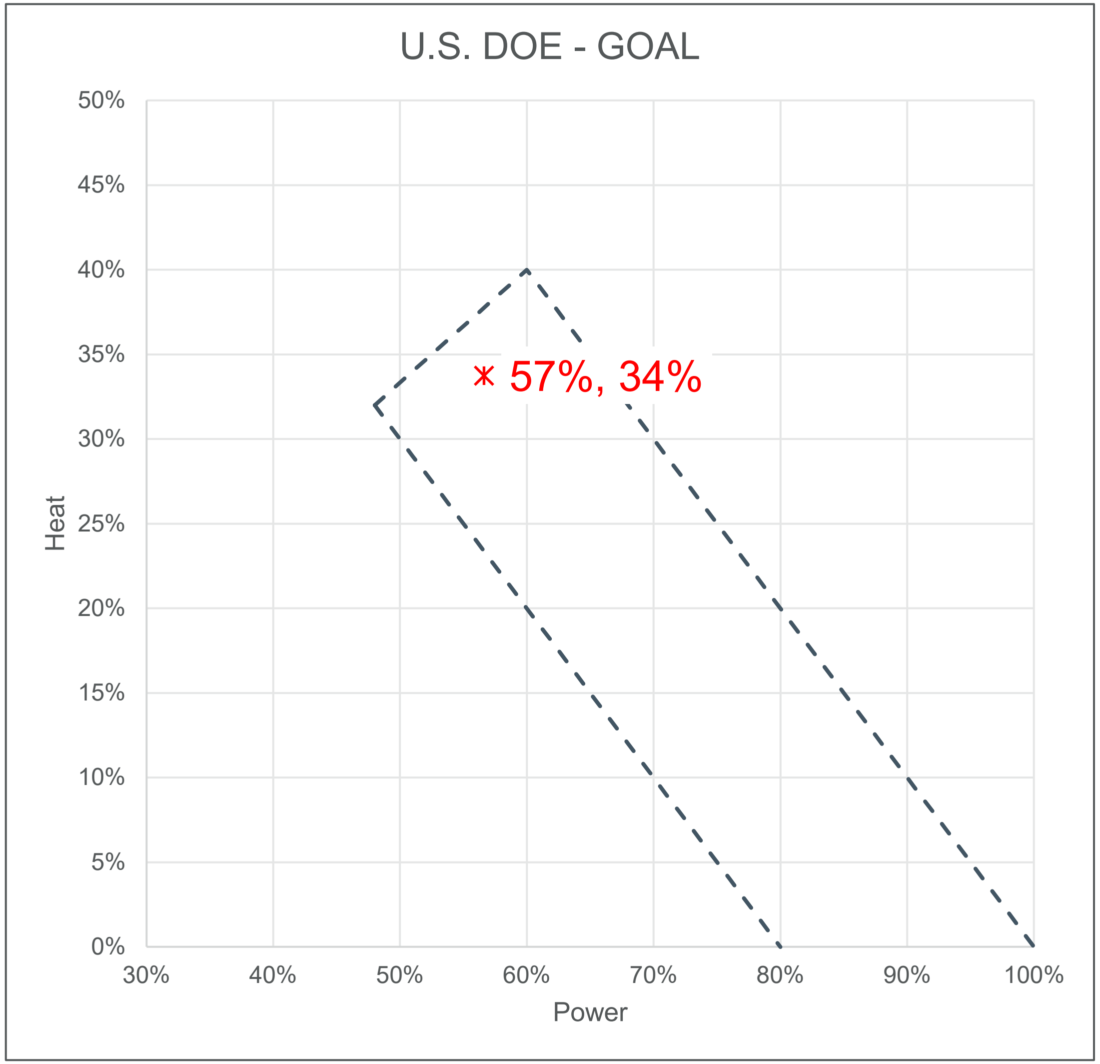


Water– Low Genset Efficiency

W_{CHP}	534.18	*kW*
$\eta_{elec\text{-}LHV}$	56.62%	%
Q_{CHP}	318.42	*kW*
$\eta_{heat\text{-}LHV}$	33.75%	%
P/H	1.68	-
$\eta_{CHP\text{-}LHV}$	90.38%	%

Overall, the Rankine cycle can increase the efficiency of the system by as much as **3%** while sharing the heat rejection to a district heating system.

Note, on this configuration, the Rankine cycle water mass flow is as low as **162 kg/hour**



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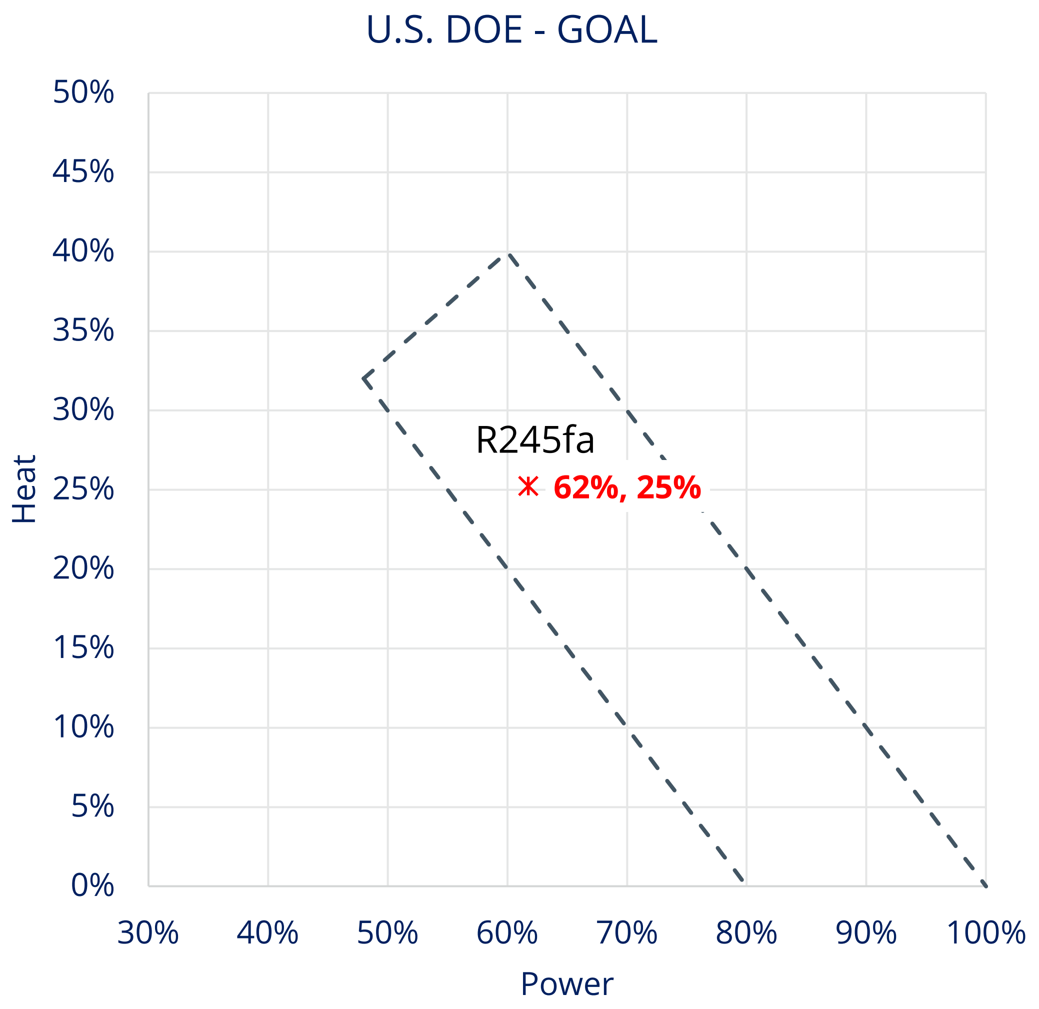
R245FA – HIGH GENSET EFFICIENCY

- The use of an ORC slightly increases the efficiency gains at low exhaust gas temperature. This increase is limited to **<2%**.
- As an example, an ORC delivers **88 kW** from a **3MW engine @60%** efficient.
- The use of an ORC reduces the heat available for DH, hurting the overall CHP efficiency of the plant compared to water.
- The 88 kW ORC and 3MW engine deliver up to **1.2MW of useful heat (@95C),** and an overall efficiency of **87%.**

In comparison, the **water cycle delivers 73 kW** of additional power, but **1.4 MW of useful heat** and an overall efficiency of **90%**



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Project Next Steps

NEXT PHASE SCOPE OF WORK STRUCTURE

Demonstrate that the thermodynamic efficiency of the RICE can be increased by as much as 18% through the integration of the APC.

Implemented in a Combined Heat and Power (CHP) framework, the goal is to show:

- RICE efficiencies as high as 65%.
- Overall system efficiency as high as 70%.

APC ENGINEERING
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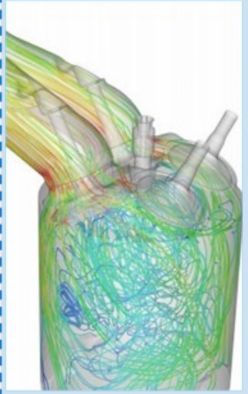
CO2 CAPTURE ENGINEERING
MTR MEMBRANE TECHNOLOGY & RESEARCH



COMBUSTION MODELING
Berkeley UNIVERSITY OF CALIFORNIA

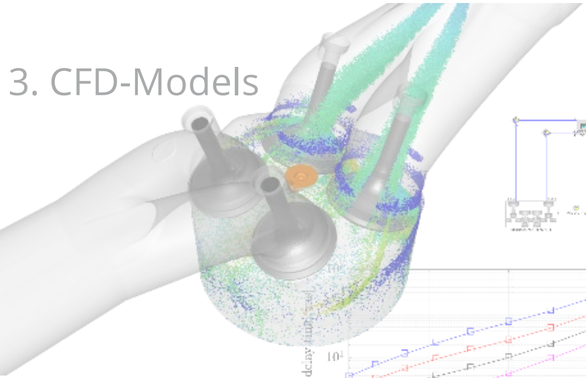
ORC MODELING
Susteon

Engine Characterization & Modification	System DP&F	Engine Operation & Optimization	Full System Integration	Full Cycle Validation & Optimization	System Optimization + Final Report
Membrane modeling, design & testing	Num. model integration & skid design	Membrane syst. construction	Membrane integration & operational support		Skid performance Analysis + Final Report
Combustion and engine modeling	Membrane + Engine model integration	Run full cycle model	Define range of feasible operation	Full-Cycle Validation & Optimization	Extrapolate Model + Final Report
Bottoming cycle scoping, Design & Model Generation		Model performance estimation	Techno Economic Analysis		Final Report preparation

Next Phase Scope of Work Structure

Numerical Modelling and System Optimization

3. CFD-Models



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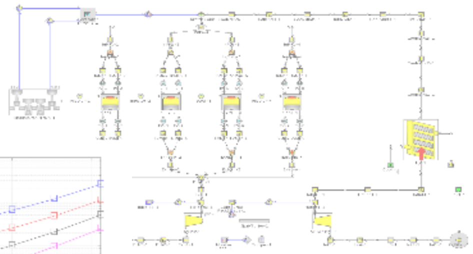

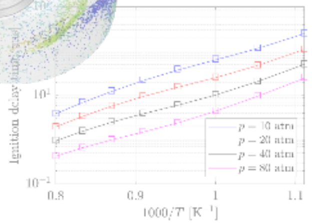

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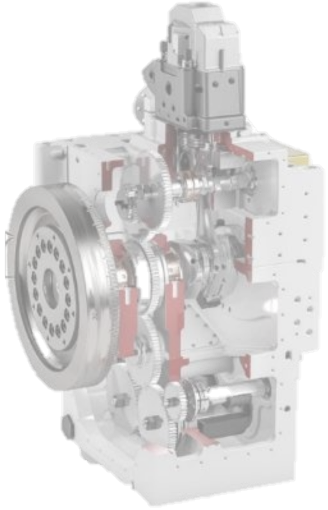
Experimental validation and optimization



Numerical Simulation

Single Cylinder (SCE) Research

Multi Cylinder (MCE) Development

Simulation and SCE results to inform MCE operation and optimization

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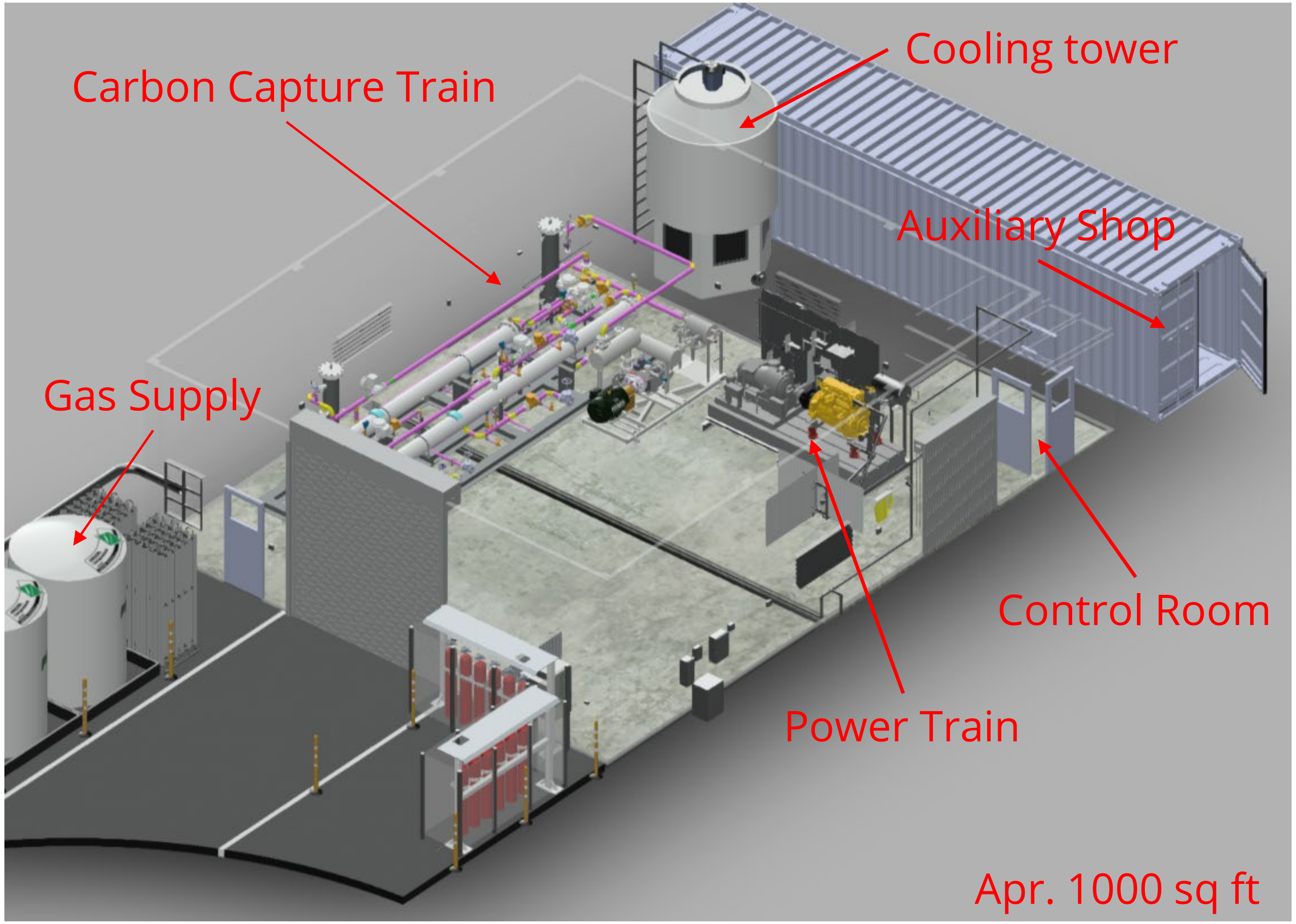
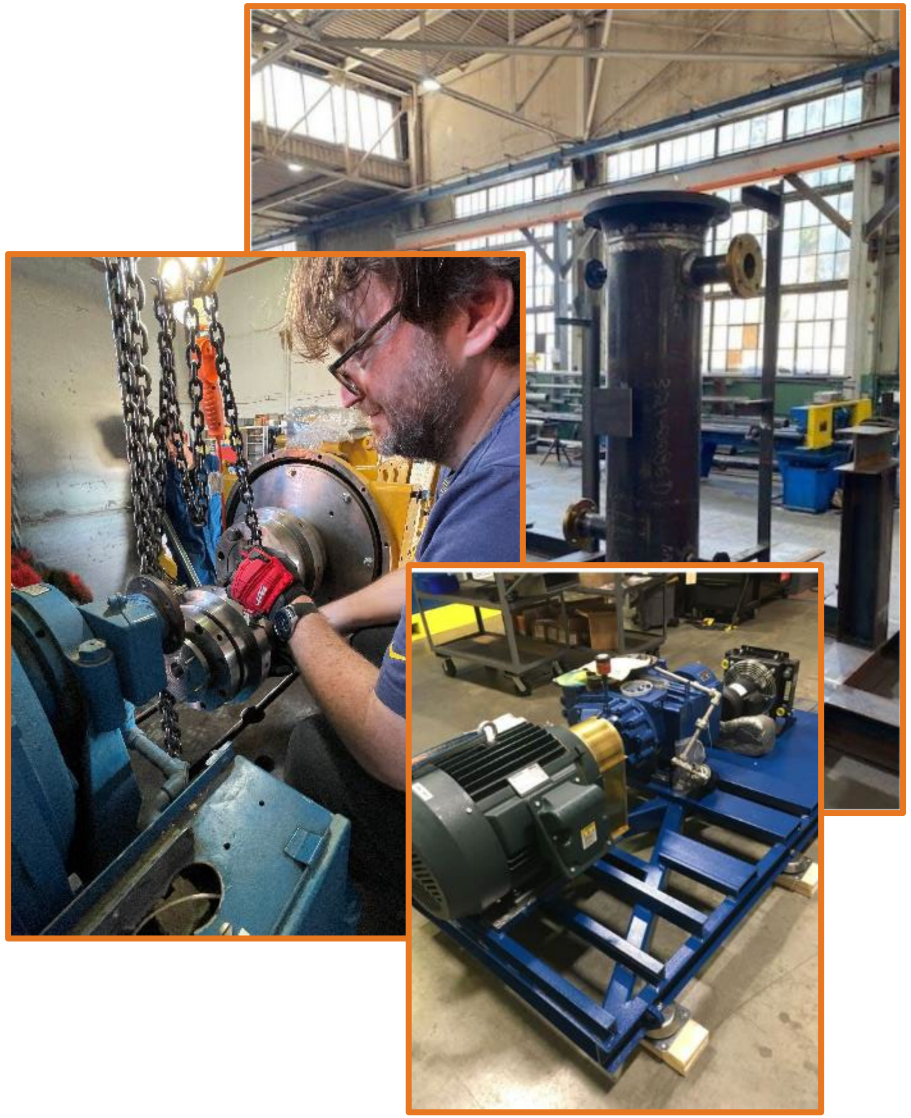
Next Phase – Coming SOON!





Miguel Sierra Aznar, PhD.
m.sierra.aznar@noblethermo.com
Noble Thermodynamic Systems, Inc.