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Comparative Analysis of Centrifugal Compressor Types for sCO_2 Applications

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Ebara Elliott Energy (We can Supply Equipment for sCO2 Power Cycles)

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Cryogenic Pumps and Expanders

- LNG or Methane (-162°C, -258°F)
- Propane (-42°C, -44°F)
- Butane (+0.6°C, +33°F)
- Ethylene (-104°C, -155°F)
- Nitrogen (-196°C, -320°F)
- Propylene (-48°C, -54°F)
- Ethane (-89°C, -128°F)
- Ammonia (-33°C, -28°F)*

Expanders and Turbines

- Single-Stage (YR) Steam Turbines
- Multi-Stage Steam Turbines
- High-Speed Turbines
- Turbine Generators

Barrel Compressors

- Axial Compressors (40,000 – 450,000 CFM Inlet)
- Centrifugal Compressors (Single Stages Overhung and Multi-stage)
  - In-line
  - In-line with side-streams
  - In-line with iso-cooling
  - Double flow
  - Back-to-back iso-cool
- Pipeline Compressors (15MW, 25MW, and 35MW)
- Flex-Op Arrangement (Multiple Bearing driven by various pinions)

Agenda

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- Various Applications for Super-Critical CO_2 Compressors
- Centrifugal Compressor Types
- Three Simple Case Studies
- Technology Challenges

Comparison of Various Compressor Types

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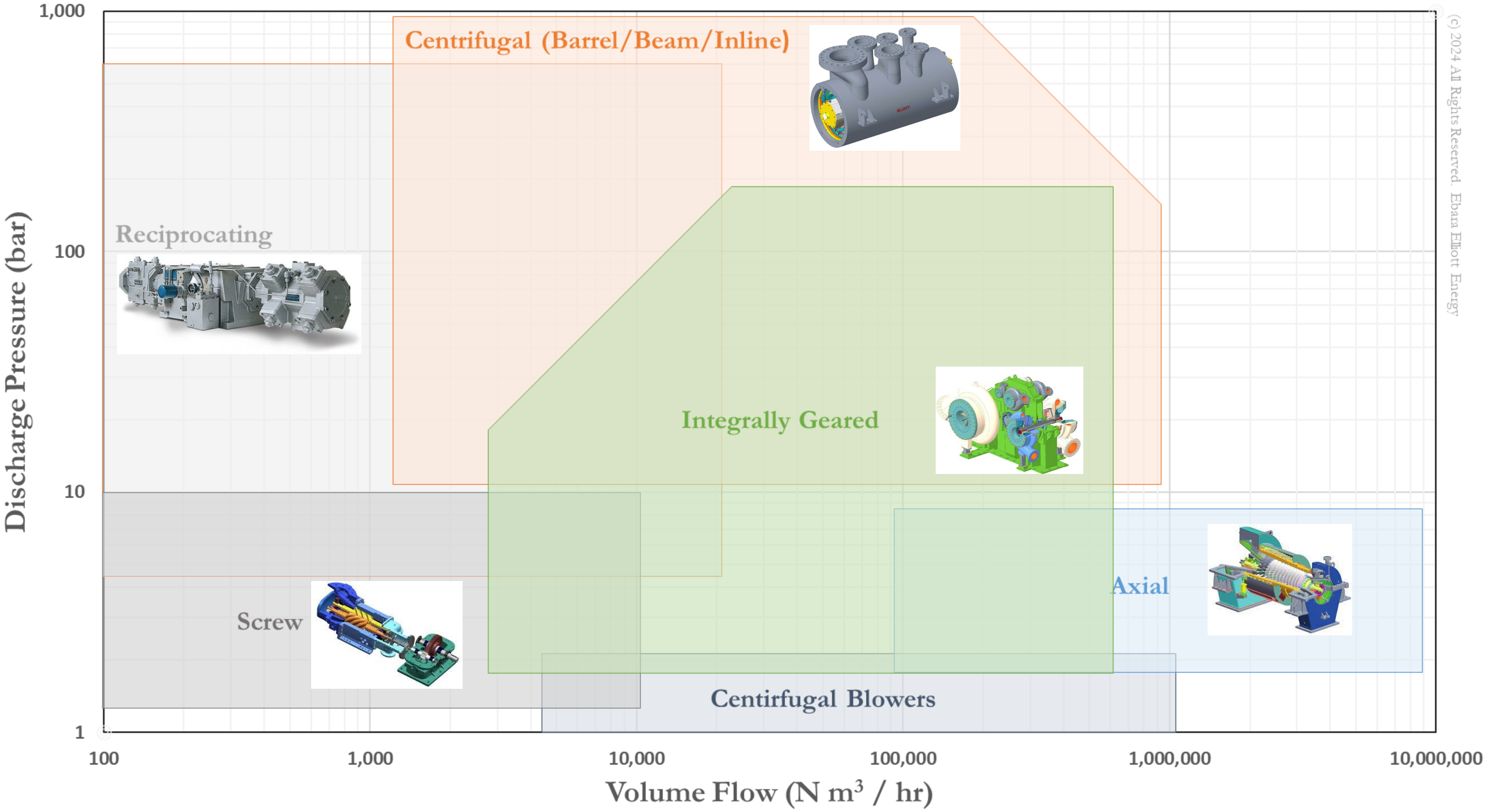

sCO_2 Systems Compared Against Machinery Type

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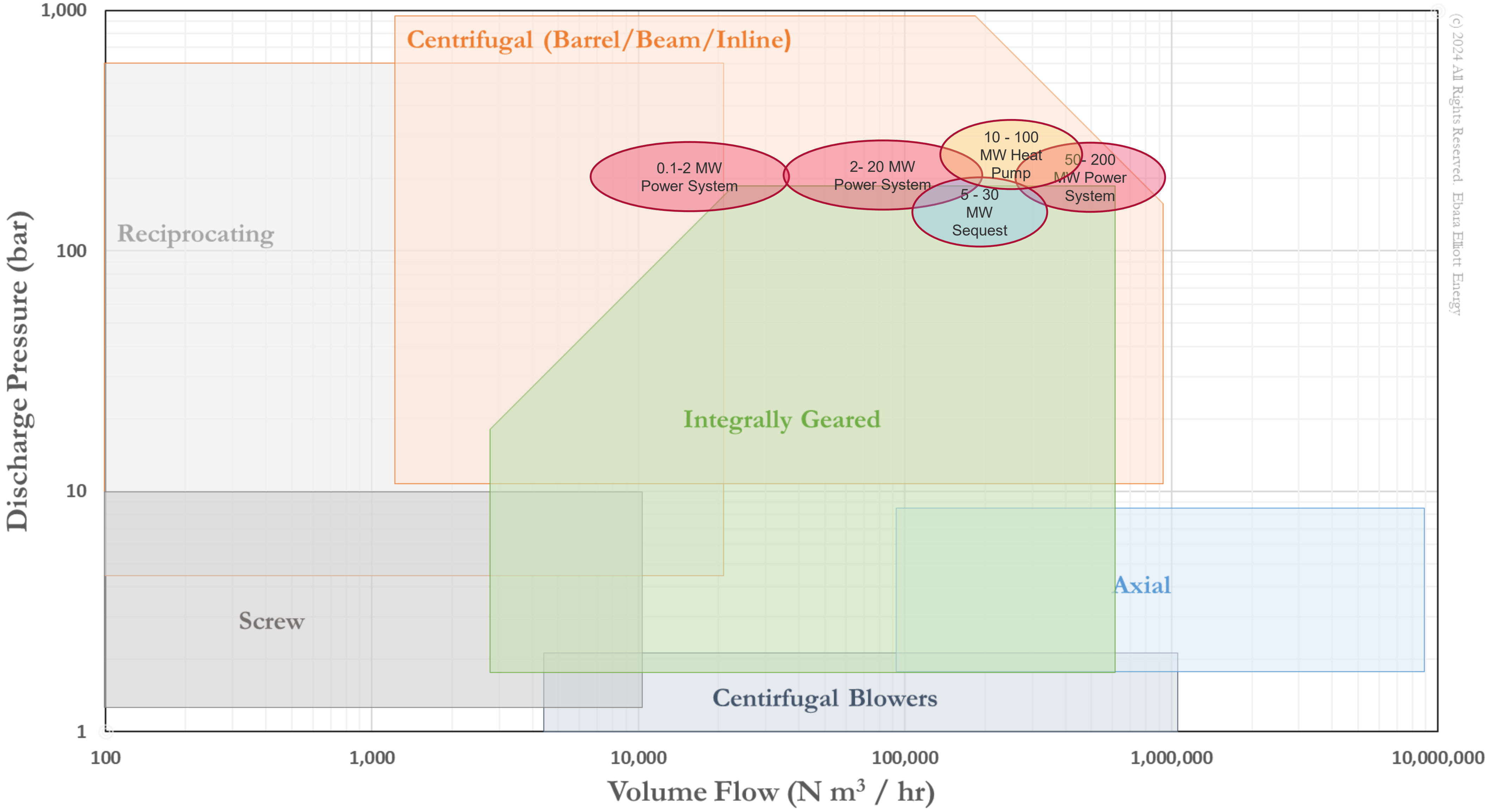

Issue for High-Power Density (sCO_2)Compressor Stages

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Geometric Variables:

Blade Taper
- Inlet
- Exit

Blade Height

Blade Thickness (b_2)

Shroud Thickness
- Constant
- Variable (Inlet to Exit)

Blade Lean
- Inlet
- Exit

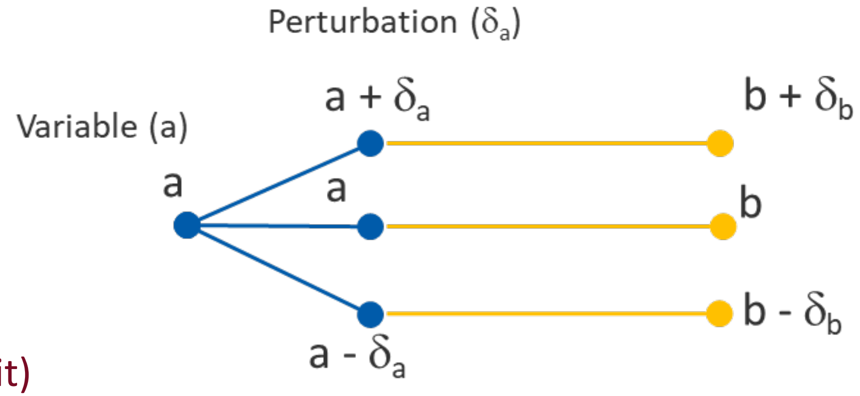
Impeller Radii (R_2)

Impeller Inlet (R_{1H})

Impeller Bore

Impeller Backface
- Thickness @ R2
- Taper Angle

Number of Blades



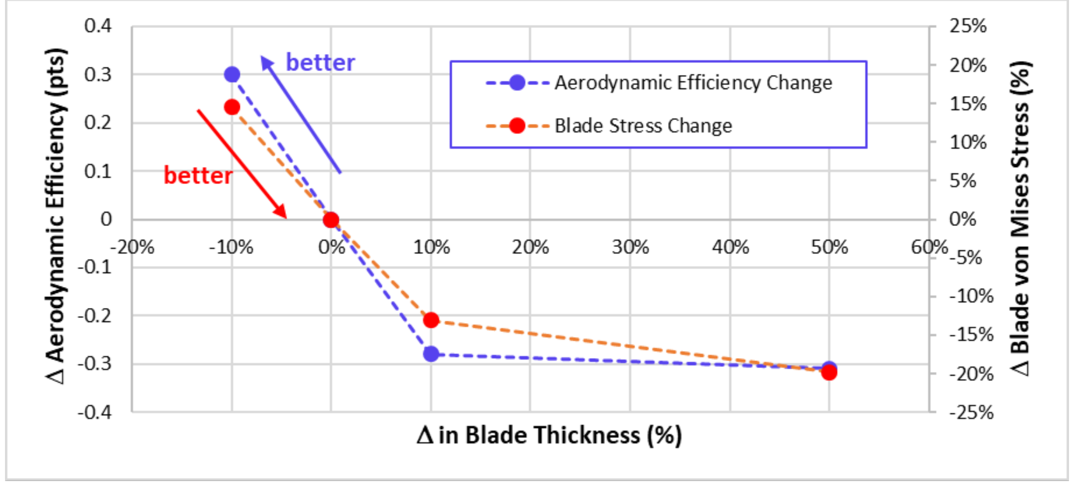
Operational Variables:

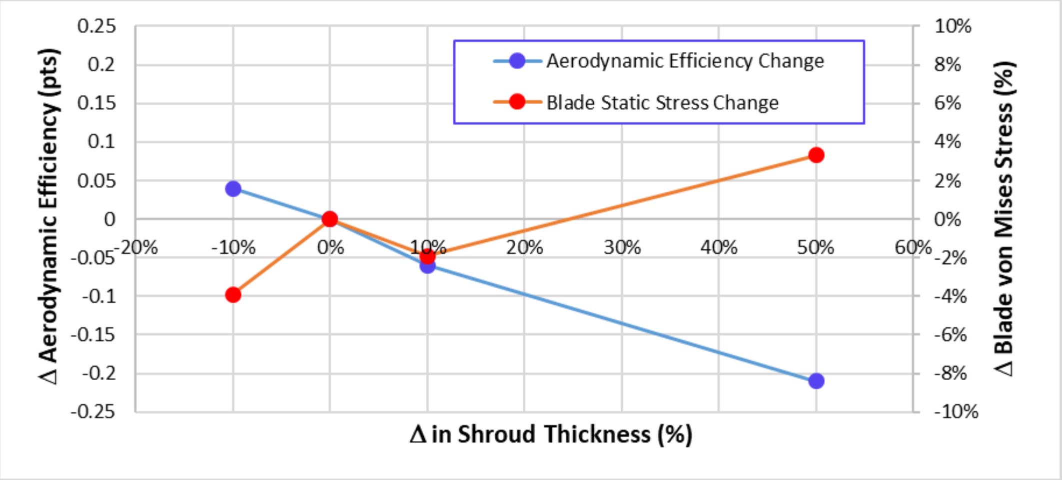
Blade Taper
- Inlet
- Exit

Blade Height

Blade Thickness (b_2)

Shroud Thickness





Primary Applications for Super-Critical CO_2 Compression

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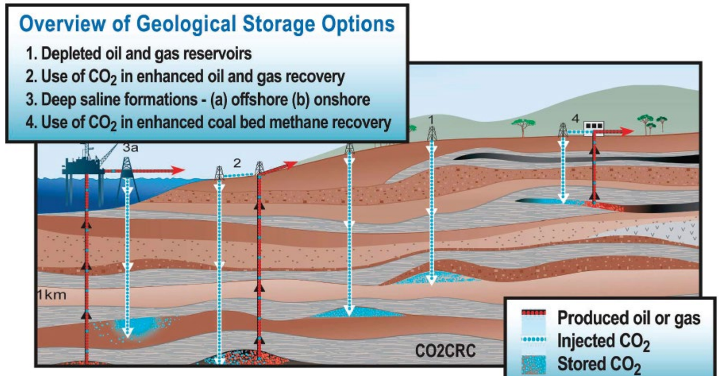
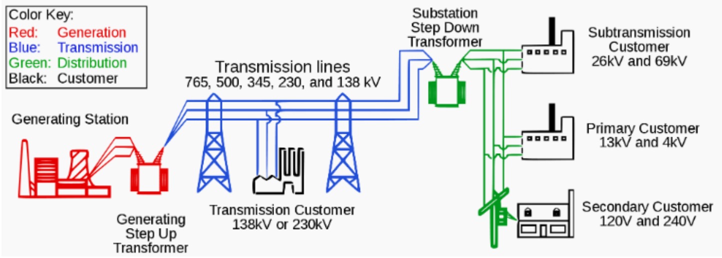
Carbon Sequestration

- **High Efficiency:** Its high density and low viscosity allow for better mass transfer, resulting in higher capture rates.
- **Lower Energy Consumption:** sCO_2 can lead to lower energy requirements for the carbon capture process
- .
- **Reduced Footprint:** The compact nature of sCO_2 systems allows for smaller equipment sizes and reduced infrastructure compared to other capture technologies.
- **Versatility:** sCO_2 can be used in a variety of carbon capture applications, including pre-combustion, post-combustion, and oxy-fuel processes.



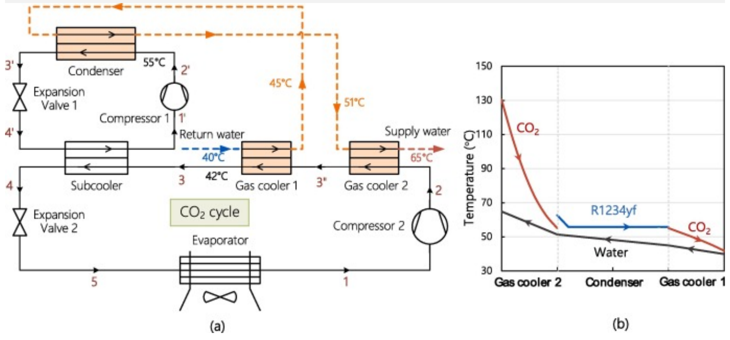
Power Systems

- **Higher Efficiency:** sCO2 power cycles operate at higher temperatures and pressures compared to steam turbines, resulting in higher thermodynamic efficiency.
- **Compact Size:** more compact than steam turbines, allowing for smaller footprint power plants. This is especially advantageous in situations where space is limited or where decentralized power generation is desired.
- **Flexibility and Load Following**: Ability to ramp up and down more quickly, making them well-suited for supporting variable renewable energy sources like wind and solar.



Heat Pumps

- **Efficiency:** Ability to operate at high pressures and temperatures, which allows for efficient heat transfer, resulting in lower energy consumption.
- **High Temperature Capability:** One of the advantages of sCO2 is its ability to reach high temperatures, making it suitable for industrial applications where high-temperature heat is required, such as in industrial processes or power generation.
- **Compact Design:** compact making them suitable for installations where space is limited. a natural refrigerant with low global warming potential (GWP) and zero ozone depletion potential (ODP).



Compression Equipment Configurations

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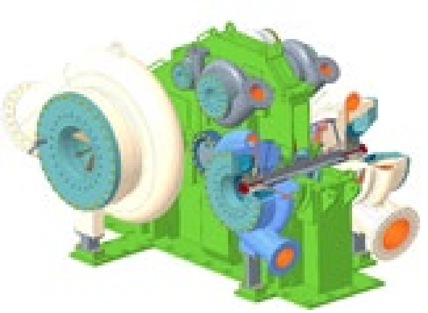
Beam Style

- **Low Maintenance Requirements:** The design of integrally geared compressors typically results in lower maintenance requirements.
- **High Reliability:** Robust configuration with minimal seals, minimal bearings, and low dynamic pressures makes for a robust design at high pressures.
- **High Efficiency at High Flow Rates**: Centrifugal barrel compressors are highly efficient at handling high flow rates. They can effectively compress large volumes of gas to moderate pressures with relatively low energy consumption.

Integrally Geared

- **Modular Design:** These compressors feature a modular design with multiple compressor stages driven by individual gears. This modular construction allows for flexibility in configuration and scalability.
- **Inter-cooling:** Ability to inter-cool each stage allows the ability to reduce power consumption by approaching.
- **Compact Footprint:** Despite their high capacity and performance, integrally geared compressors have a relatively compact footprint compared to other types of compressors with similar capabilities.



Reciprocating

- **High Compression Ratios:** Reciprocating compressors are capable of achieving high compression ratios, making them suitable for applications requiring high-pressure delivery.
- **Cost-effectiveness for Small to Medium Applications**: Generally more cost-effective for small/medium applications. They have lower initial capital costs and are simpler in design.
- **Efficiency at Low Flow Rates**: Reciprocating compressors excel at handling low flow rates efficiently. Suitable for applications where variable demand is common or where the compressor needs to operate at different flow rates.

CO_2 Sequestration

Carbon Capture and Sequestration Value Chain

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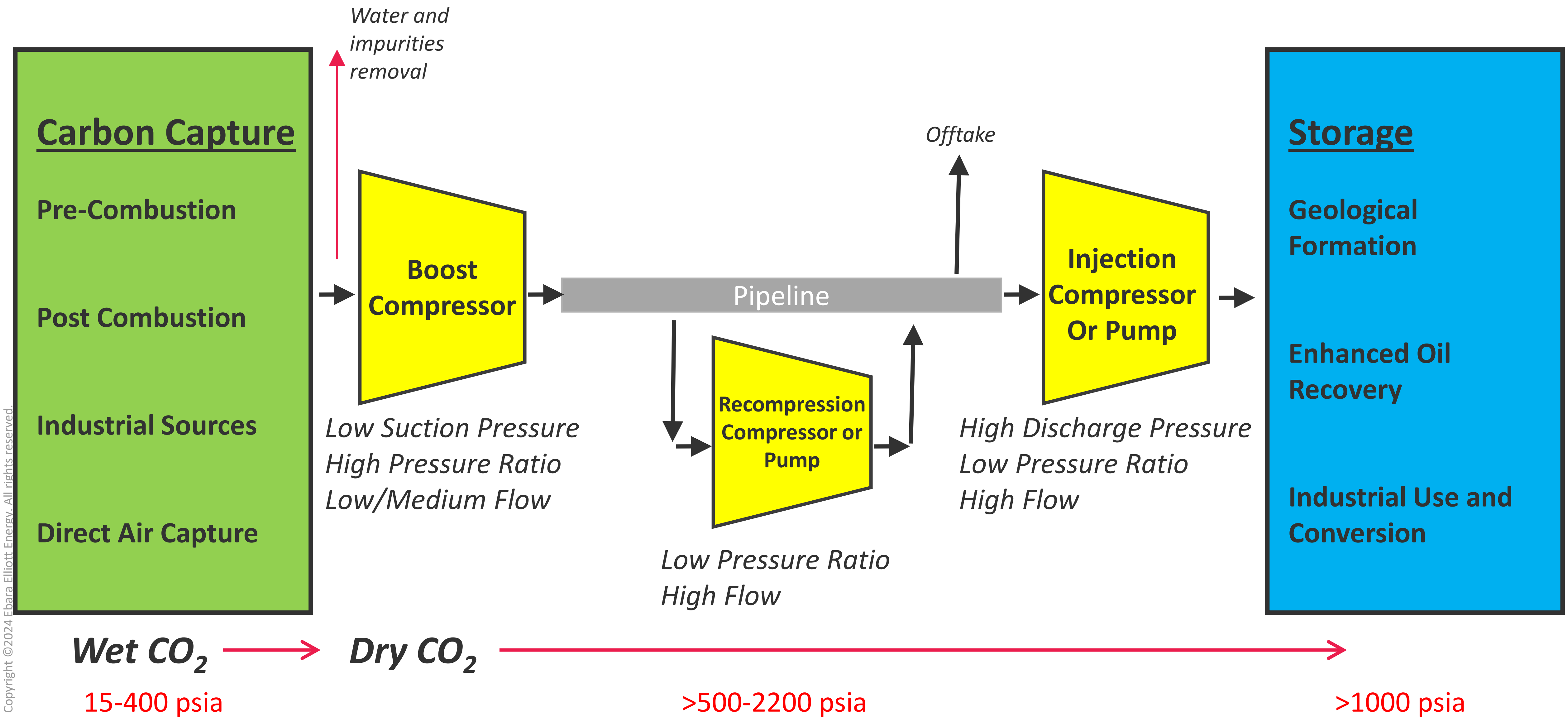

Case Study – CO_2 Sequestration Compressor

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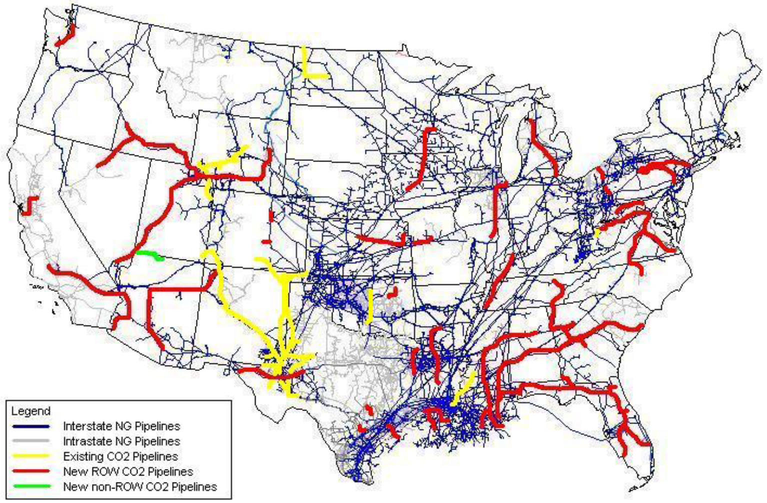
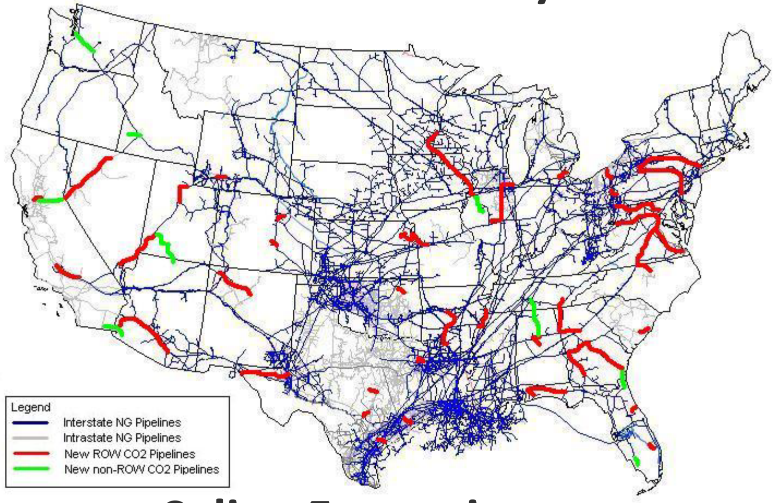
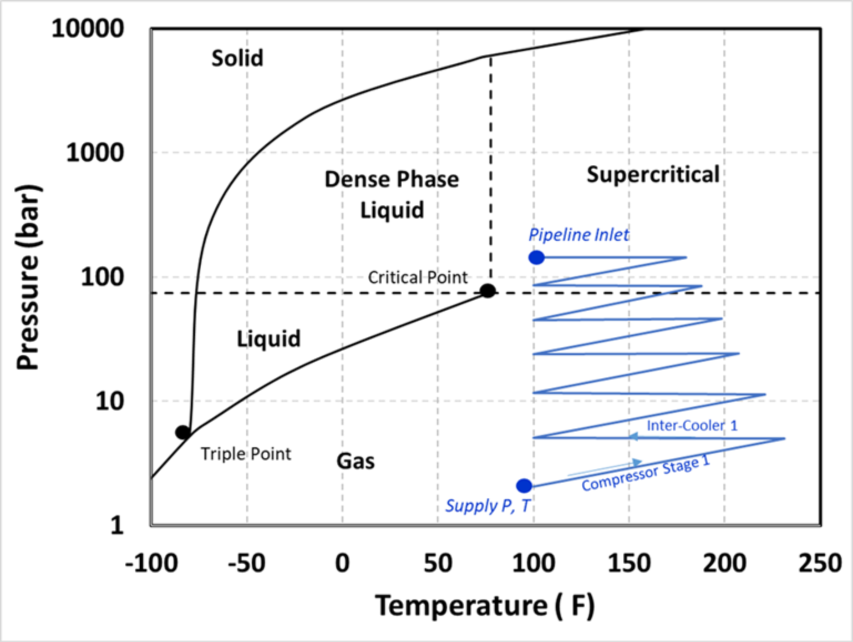


Enhanced Oil Recovery



Saline Formations

Plenty of storage capacity and options, but do not align geographically with likely CO_2 production sites



Supply Pressure	atm
Supply Temperature	100 F
Discharge Pressure	2200 psia
Discharge Temperature	100 F
Supply Flow	67.7lbm/s

Case Study – CO_2 Sequestration Compressor

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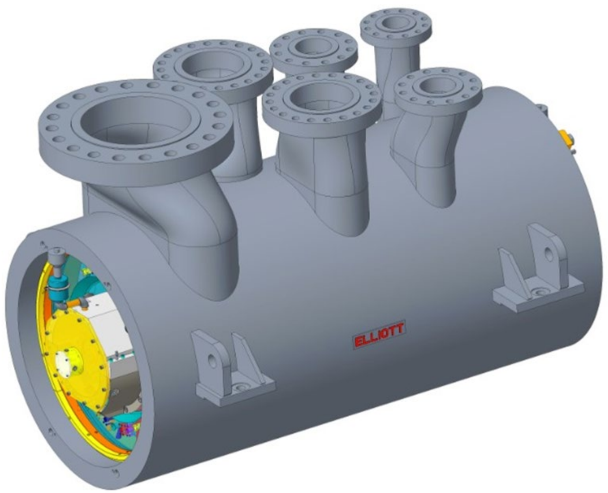
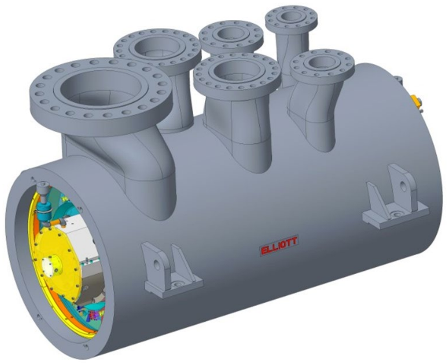
LP Section

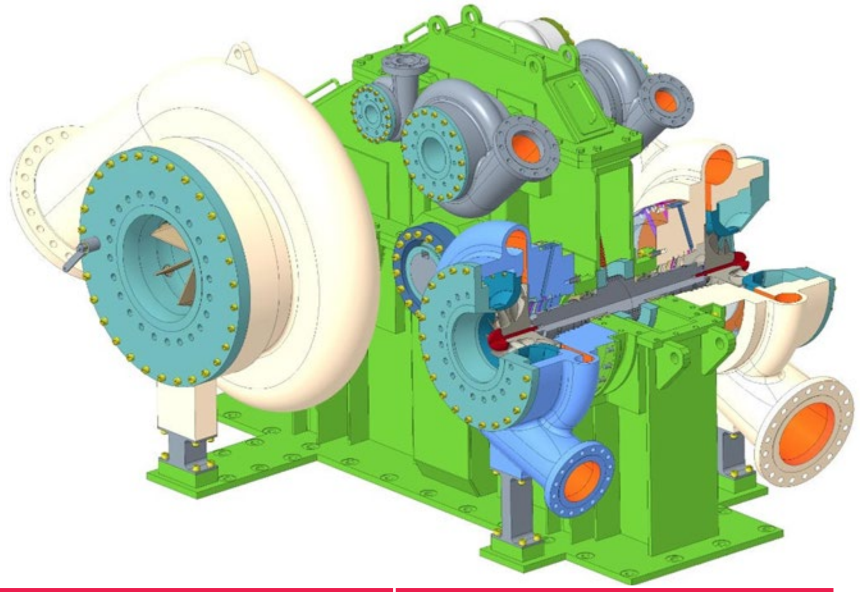


HP Section



Type	Beam Style (2 Bodies)
Drive	Induction Motor
Inter-Stage Coolers	3
Gas Seals	4
Gear Boxes	2
Journal Bearings	4 for Compressor 8 for Gearboxes
Drive Power	12,863 kW

"strong point"



Type	Integrally Geared
Drive	Induction Motor
Inter-Stage Coolers	6
Gas Seals	7
Gear Boxes	1
Journal Bearings	16 Total
Drive Power	10,925 kW

"strong point"

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sCO_2 Heat Pumps

Case Study – sCO_2 Heat Pump for Steam Generation

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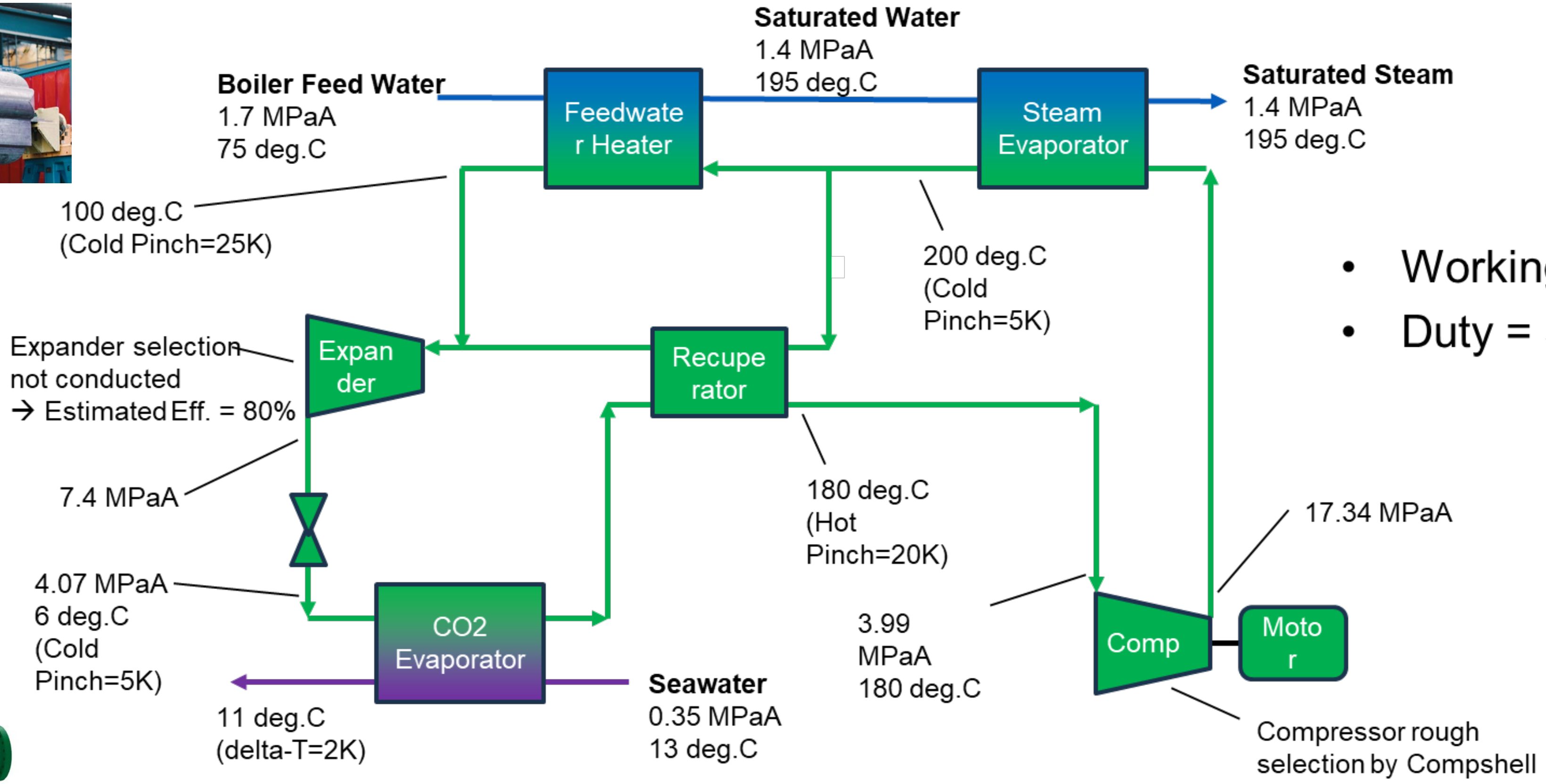
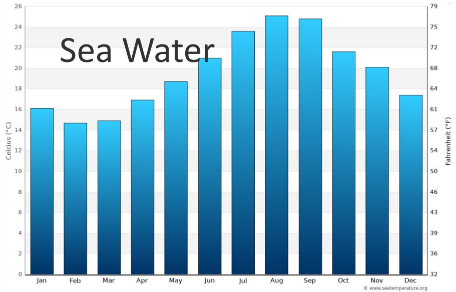
Recuperator



- Working fluid = CO2
- Duty = 3,800 kW

JT Valve



Compressor

Case Study – CO_2 Heat Pump

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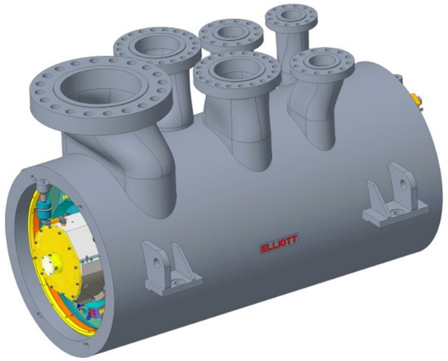
Two Section (Four Stage) Barrel



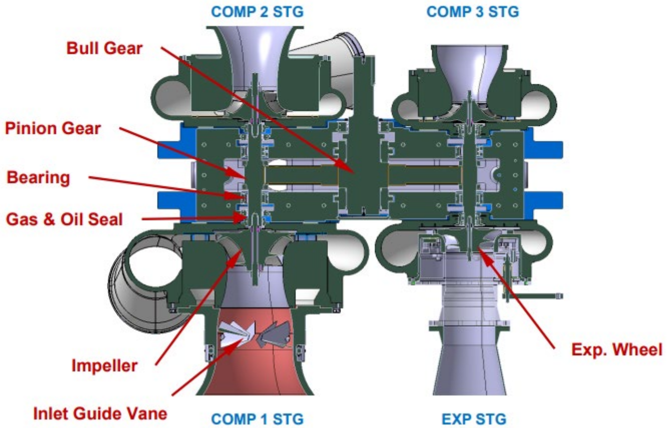
Supply Pressure	3.99 MPaA
Supply Temperature	180 C
Supply Flow	12.95 kg/Sec
Discharge Temperature	304 C
Discharge Pressure	17.34 MPaA
Gear Boxes	1
Number of Stages	4
Journal Bearings	2 Compressor 4 Gearbox
Number of Seals	2
Drive Power	2,673 kW

"strong point"

Four Stage Integrally Geared

Supply Pressure	3.99 MPaA
Supply Temperature	180 C
Supply Flow	12.95 kg/Sec
Discharge Temperature	304 C
Discharge Pressure	17.34 MPaA
Gear Boxes	1
Number of Stages	4
Journal Bearings	6
Number of Seals	4
Drive Power	2,395 kW

"strong point"



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sCO_2 Power Systems

Case Study – CO_2 Power System

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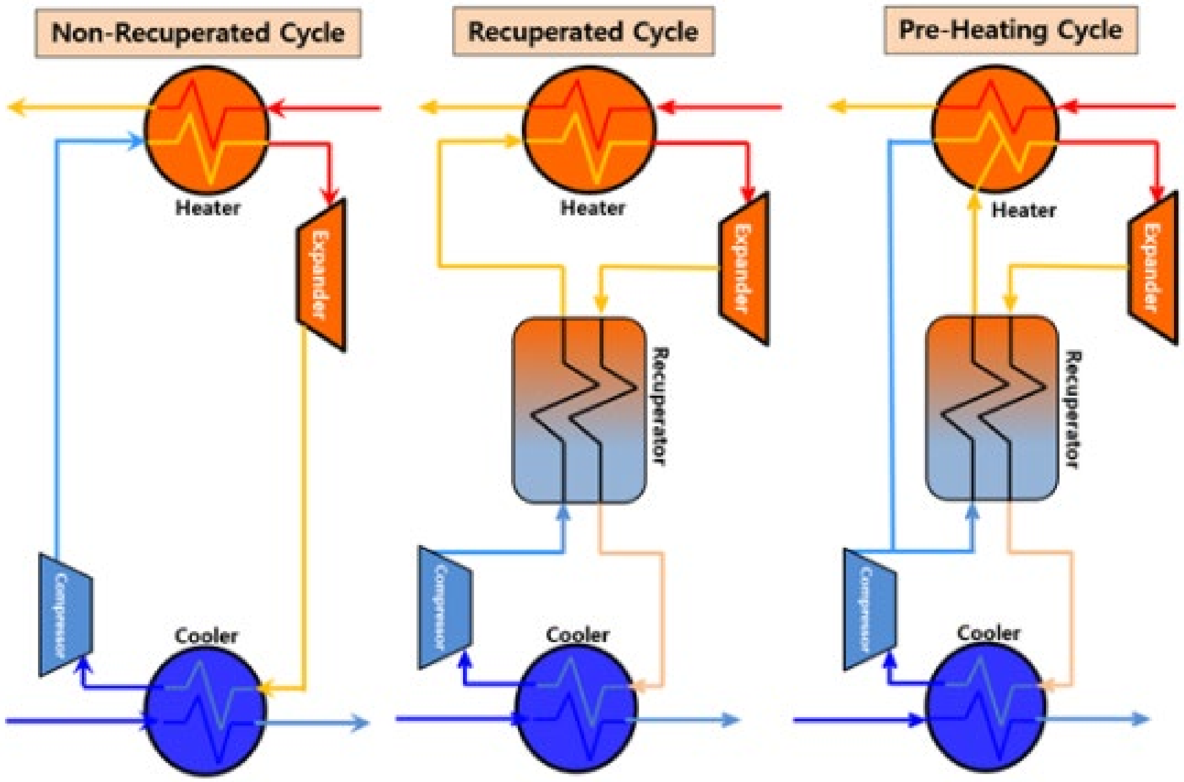
- Range of Cycles from: Simple, Recuperated, Preheating, recompression, re-heat, etc.
- Applications are also varied from: Nuclear, CSP, to WHR.
- Power Levels vary by application. This makes a single case study potentially biasing.
- Key point is that you are not pressuring from atmosphere to Super-critical zone.



Three Cycles for sCO2 of WHR of Gas Turbine

Case Study – CO_2 Power System

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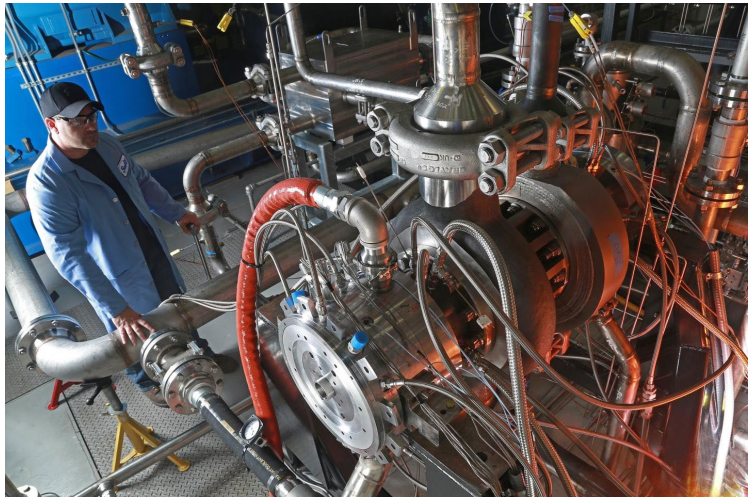
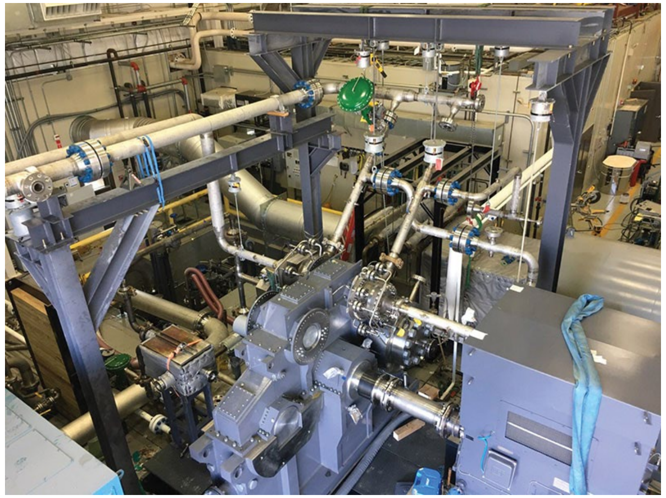
Barrel Compressor (Recompression Cycle)



Ideal Design Space	>10MW
Compressor	2 stages
Recompressor	2 stages
Gearboxes	2
Seals	4 seals
Controls	Separate compressor/Recompressor/

Integrally Geared (Recompression Cycle)



Ideal Design Space	2-to-25MW
Compressor	2 stages
Recompressor	2 stages
Gearboxes	1
Seals	4 seals
Controls	Integrated mechanical system can complicate controls

Compression Options for MW Scales

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	Integrally Geared Compressor	Beam Style Compressor
Sequestration (Open Loop System)	**OPEX:** Strong advantage for IG style.	**Reliability:** Reduced number of gas seal points is advantage for barrel configuration.
Power System (Closed Loop System)	**Modularity:** over-hung stages allow ability to quickly adjust design in development or test stand. **Wide Operating Range**: ability to apply range extension technologies. **Expander Stage Integration:** Can integrate expander. Good for 2-25 MW (WHR)	**Mature Technology:** for high-pressures. **Hermetic Seal Potential:** Ability to seal against lower pressures. **Mechanical Losses:** fewer number of bearings and reduced losses. Good for 10-200 MW (Nuclear/Power Gen)
Heat Pump (Closed Loop System)	**Similar to Power System**	**Similar to Power System**

Technology/Risk Areas to Address

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	Integrally Geared Compressor	Beam Style Compressor
Sequestration (Open Loop System)	Mature Technology. Seal Improvements for Leakage.	CAPEX and OPEX tend to be higher than IGC.
Power System (Closed Loop System)	Seal Improvements for improve reliability and leakage reduction. Limited data near critical point.	Gas Bearings/ Magnetic Bearing for seal-less systems. Limited data near critical point.
Heat Pump (Closed Loop System)	Similar to Power System	Similar to Power System

Thank You!