NATIONAL ENERGY TECHNOLOGY LABORATORY

Session 5: Low Carbon Power Generation

Transformational Power Generation

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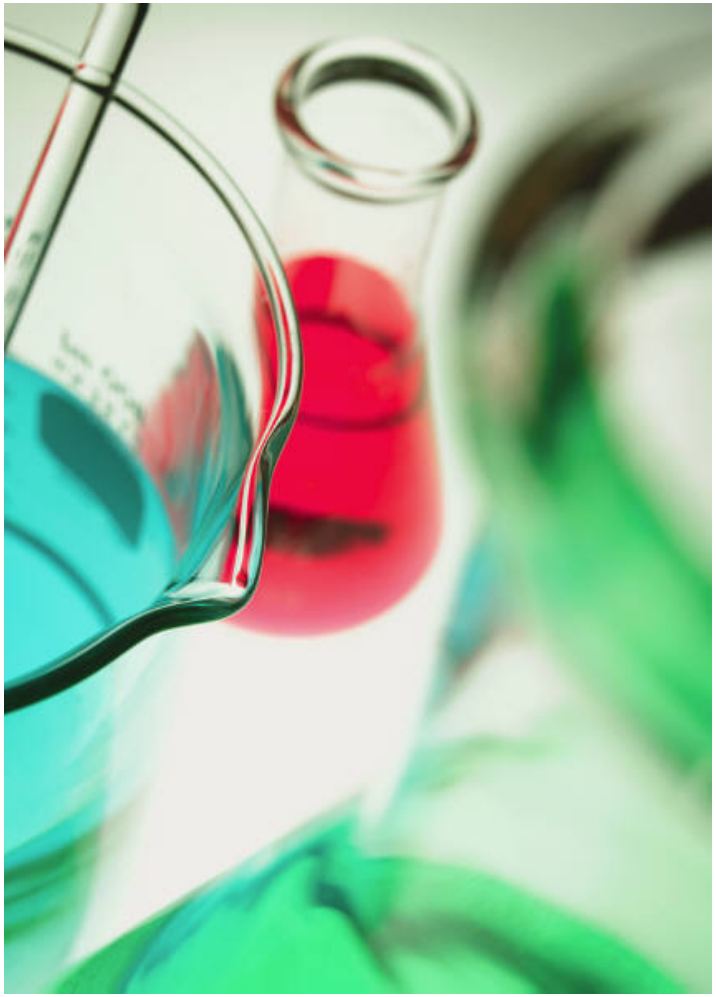
NETL Office of Research and Development

Transformational Carbon Capture Technology Workshop
September 23 – 24, 2014, Arlington Virginia

U.S. DEPARTMENT OF ENERGY

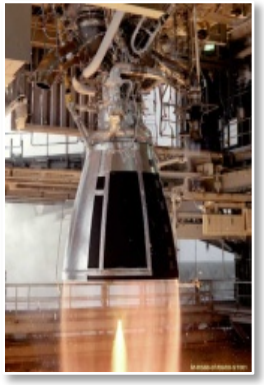
Transformational?

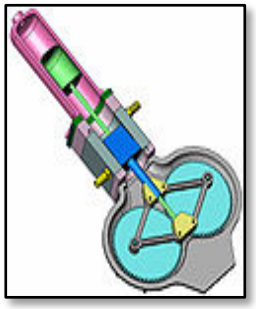
- A technology that you would develop even if there was not need to capture carbon dioxide.
- A step-change in generating efficiency from a single technology.
- A different approach to regenerating carbon capture media.



Options *across* the *temperature spectrum.*

- **Most electric power originates from the middle of the temperature "spectrum" (below).**
- **Can we exploit the temperature spectrum in new ways?**





Oxy-fuel (~3000˚C)

Combustion Engines (~1700˚C)

Steam Turbines (~600˚C)

Specialized Cycles (<600˚C)*

Today

Propulsion | *Electric Power and Transportation* | *Geothermal power*

3000 ˚C — ***200 ˚C***

Future

Direct Power Extraction:
Making oxy-fuel an advantage with CO_2 capture

Pressure Gain Combustion:
Increased generating efficiency offsets carbon capture penalties

Electrochemical Heat Engines:
A new approach to heat recovery and energy storage

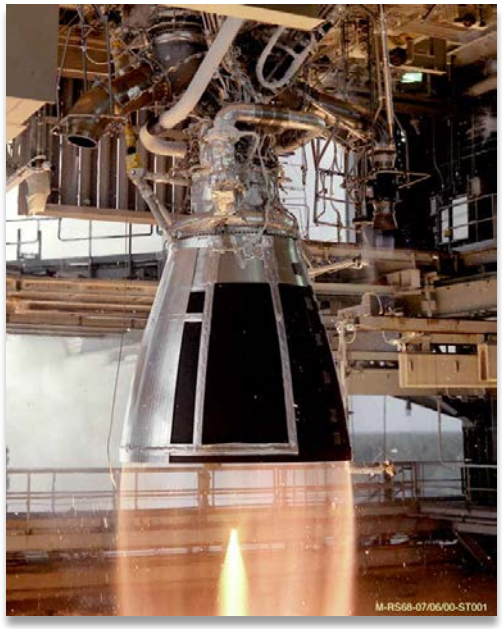
Combined fossil and geothermal generation:
Low-temperature geothermal with high performance

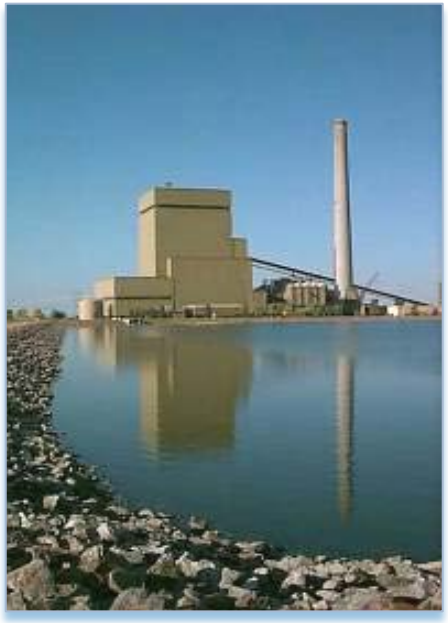
**Specialized cycles include organic rankine, stirling engines, supercritical CO_2 and others*

Figure permitted for use by http://en.wikipedia.org/wiki/Stirling_engine

Making Oxy-fuel an ***Advantage***

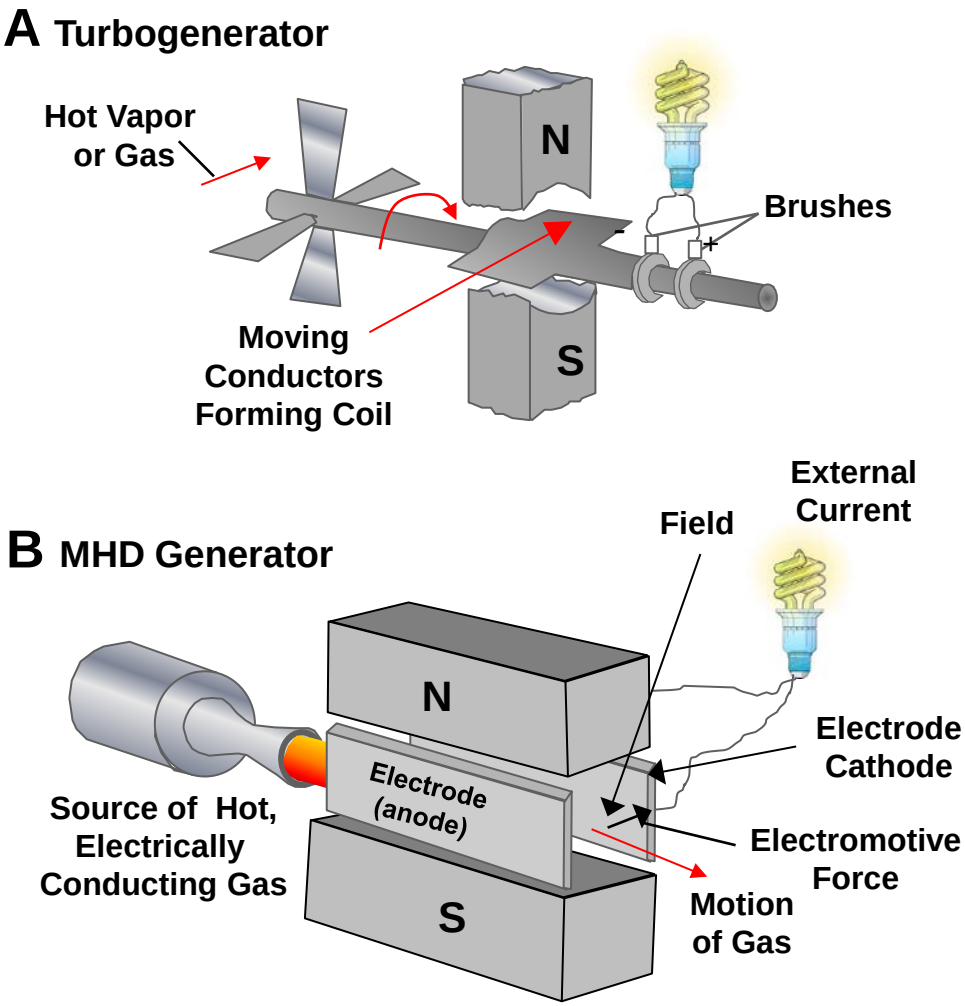
- **Producing pure oxygen requires a lot of energy!**
- **If one could find a way to make significant extra power *because of the available oxygen*, *oxy-fuel would be an advantage.***
- **Oxy-fuel already provides an advantage for process industries that benefit from high temperatures (e.g., glass making, steel).**
- **Oxy-fuel already provides advantages in propulsion (rocket engines)**
- **How can you make oxy-fuel an advantage for power generation?**





Magnetohydrodynamic Power Generation

- **The high temperatures possible with oxy-fuel can be used to operate an MHD "topping" cycle:**
  - Topping cycle power possible *because of the oxygen*
  - MHD exits to conventional steam boiler system ("bottoming cycle").
- **How does MHD work?**
  - Conductive, high-temperature gases play the role of an electrical conductor moving through a magnetic field.
  - Generates power directly from the moving gases.



Significant DOE program in 1980's, before carbon capture…..what's different?

The “new” MHD: making oxy-fuel an advantage

New benefits, new approaches, new technology:

Legacy MHD program	Today	Comments
No CO_2 capture	CO_2 Capture	Oxy-fuel combustion developed for capture enables MHD.
Large demos	Simulation & validation	Validated models for different generator concepts, not demos.
Pre-heated air	Efficient oxygen production	ASU power requirements have dropped 40% since 1990.
SOx and NOx control	Capture GPU	No emissions! Use oxy-fuel gas processing unit (GPU).
Magnets < 6 Tesla	Magnets > 6 Tesla	Advanced magnets exist today.
Analog electronics	Solid-state inverters/control	Electrode arcing could be controlled with digital devices.
Linear generator	Radial, Linear, others	Simulations can compare multiple geometries.
Conventional manufacturing	Advanced manufacturing	New channel construction approaches.
Seeded flows	New goal: injected plasma	Aspirational – use nanosecond pulse discharge to ionize gas ?

More details - Workshop

Workshop specifically devoted to this topic, next week:

2014 Magnetohydrodynamics Power Generation Workshop

Dates: October 1-2, 2014
Venue: Crystal Gateway Marriott
Open to US citizens

For questions regarding conference logistics, please contact:

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NETL Event Management
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(412) 386-4763
karen.lockhart@contr.netl.doe.gov

We look forward to your participation and comments!

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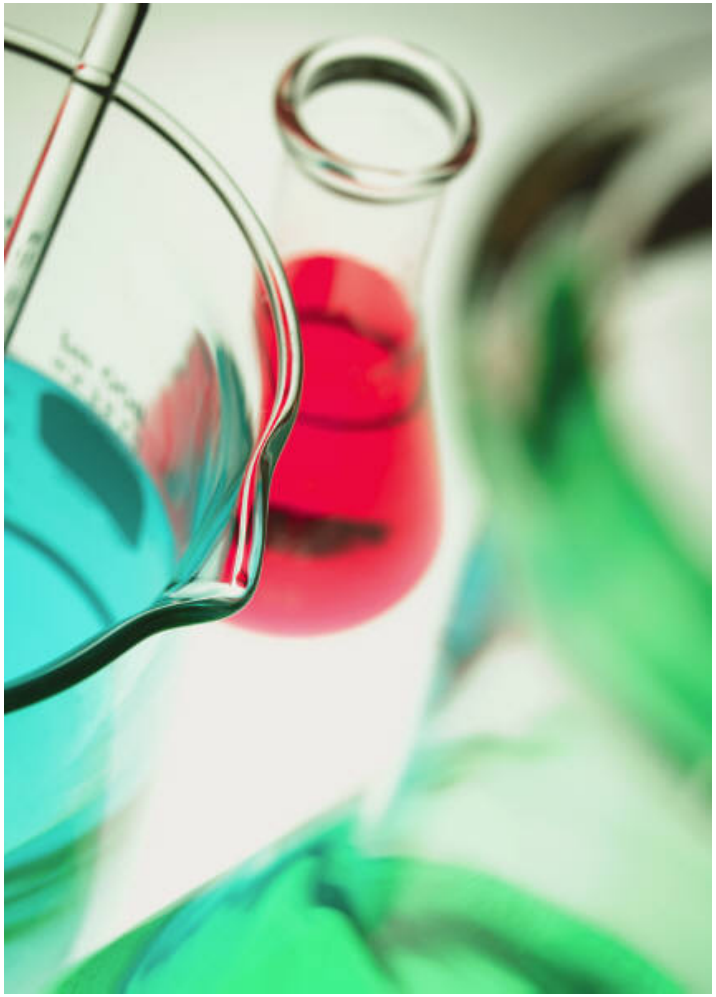


History and Turbine Efficiency

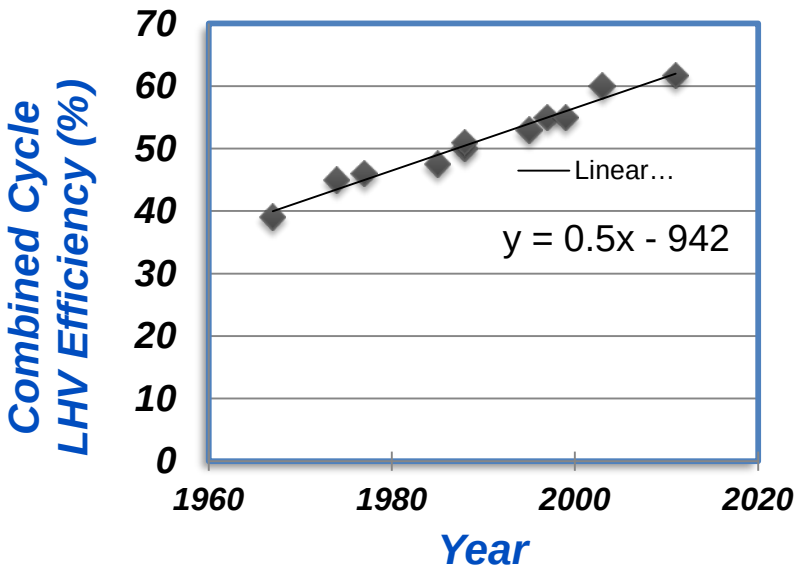
- **Combined Cycle Gas Turbine Efficiency is today + 61% (LHV).**
- **Efficiency gains have occurred with steady progress in materials, heat transfer, and system design.**
  - About +0.5 % per year (right).
- **Impressive performance is still well-below potential:**

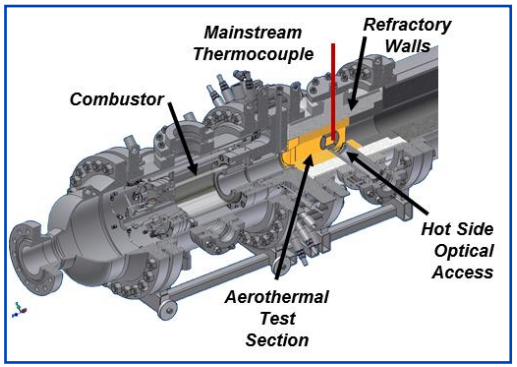
$$\eta_{\text{Carnot @ 1600C}} = 1\text{-}293/(1873) = 84\%$$

~ State of the art turbine inlet temperature

- **What can be done to "jump above" the line?**

*Gas turbine efficiency trend**





Test rig for advanced aerothermal cooling development

** Sources: (1) Herzog, H., Unger, D. (1998) Comparative Study on Energy R&D Perfrmance: Gas Turbine Case Study, Final Report for Central Research Institute of Electric Power Industry (CRIEPI), Figure B, pp. iii. , http://web.mit.edu/energylab/www/pubs/el98-003a.pdf (2) Gas Turbine World 2012 Performance Specs, 28th ed Vol 42, No1, pp 31.*

Pressure Gain Combustion
A different thermodynamic cycle

Constant-volume combustion products are at a significantly greater thermodynamic availability than constant-pressure.

30 bar, 600 K

30 bar, 1600 K

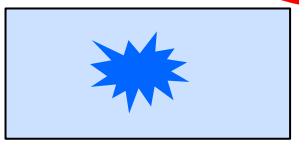
Conventional steady combustion (~constant pressure)

$$\Delta H = Q$$

$$C_p \, \Delta T_{cons\ P} = Q$$

30 bar, 600 K

100 bar, 2000 K



Pressure -gain combustion (~constant volume)

$$\Delta U = Q$$

$$C_v \, \Delta T_{cons\ V} = Q$$

Take-away:

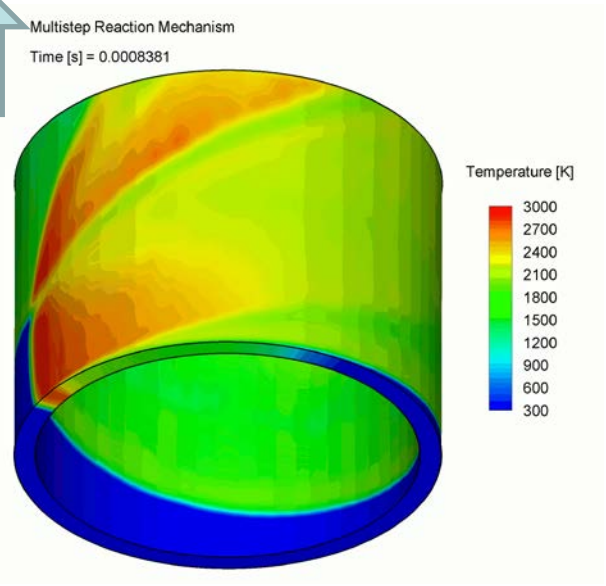
If you confine combustion, the products have more available energy versus allowing unrestrained expansion.

Rotating detonation – efficiency from confined combustion

Higher pressure, ~ steady flow to turbine

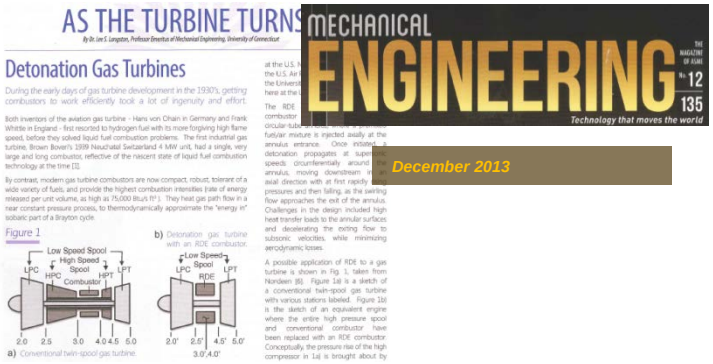
Rotating Detonation

Inlet from compressor



Rotation rate ~ 5 kHz

- ***Rotating wave confines the combustion and leads to pressure gain.***
- ***Diffusion to the exit produces a nearly steady exhaust.***
- ***Significant turbine efficiency gains are projected (see below).***
- ***Development in progress with multiple agencies and applications (AFRL, ONR, NASA, NETL, ARPA-E).***
- ***Interesting point for carbon capture – the process is "easiest" with hydrogen.***



ASME Mechanical Engineering Magazine, Image used with permission

Gas Turbine World
Pequot Publishing
Nov – Dec 2013 issue

Pulse detonation for 65% plant efficiency
Page 20

Image used with permission of Gas Turbine World

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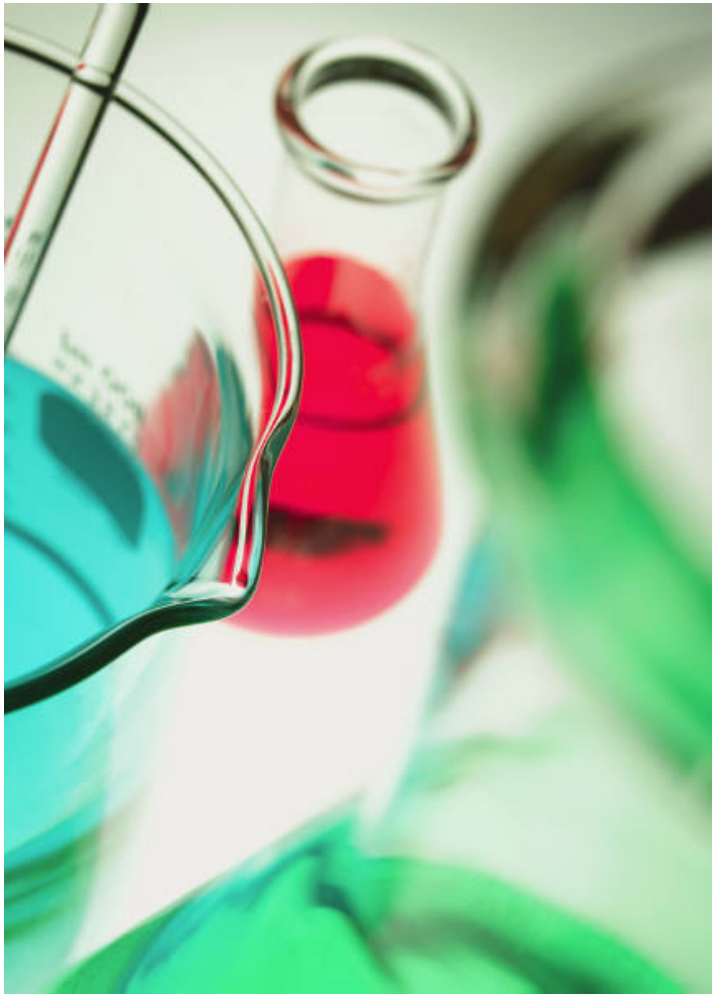
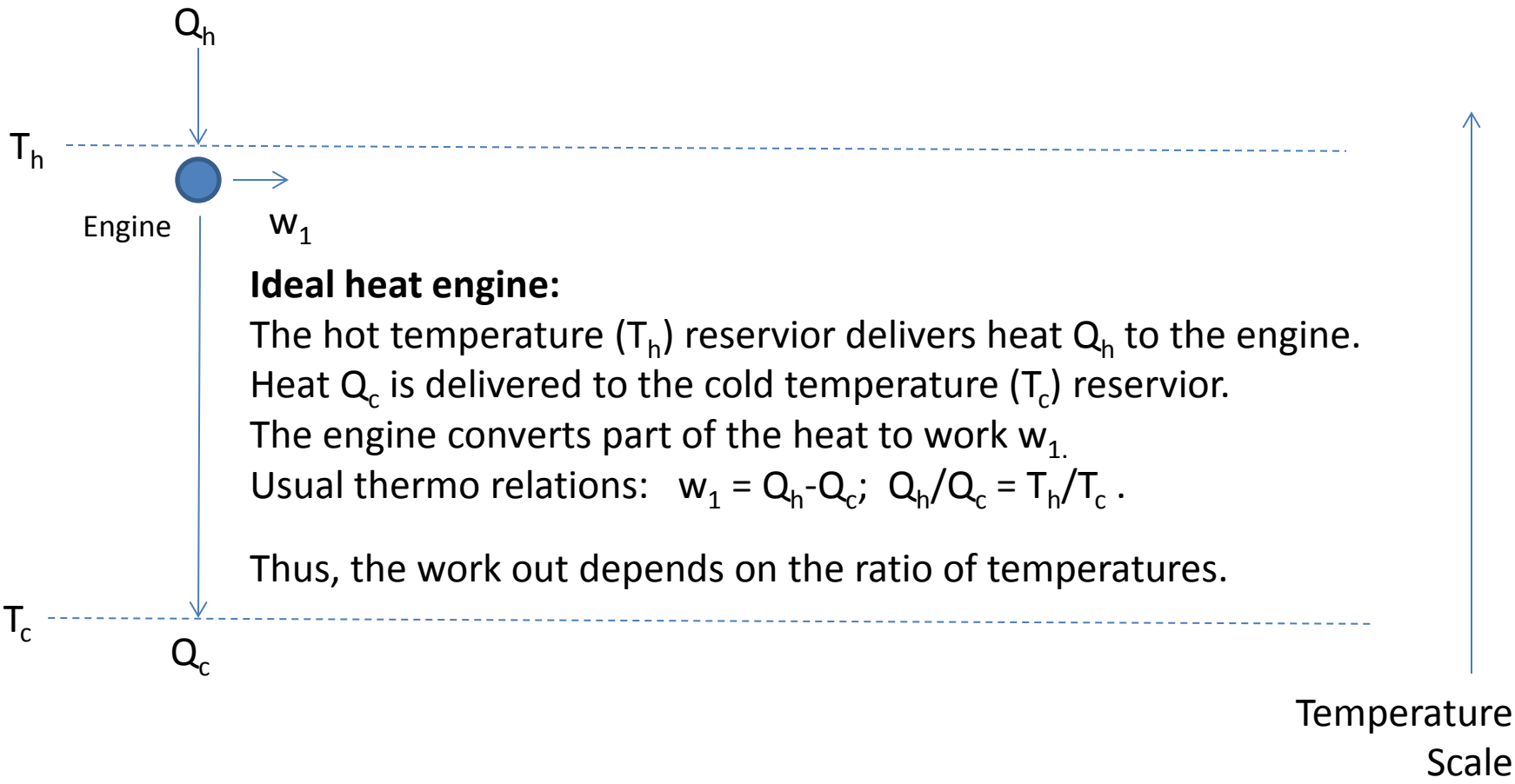


Description of an ideal heat engine



Ideal heat engine:

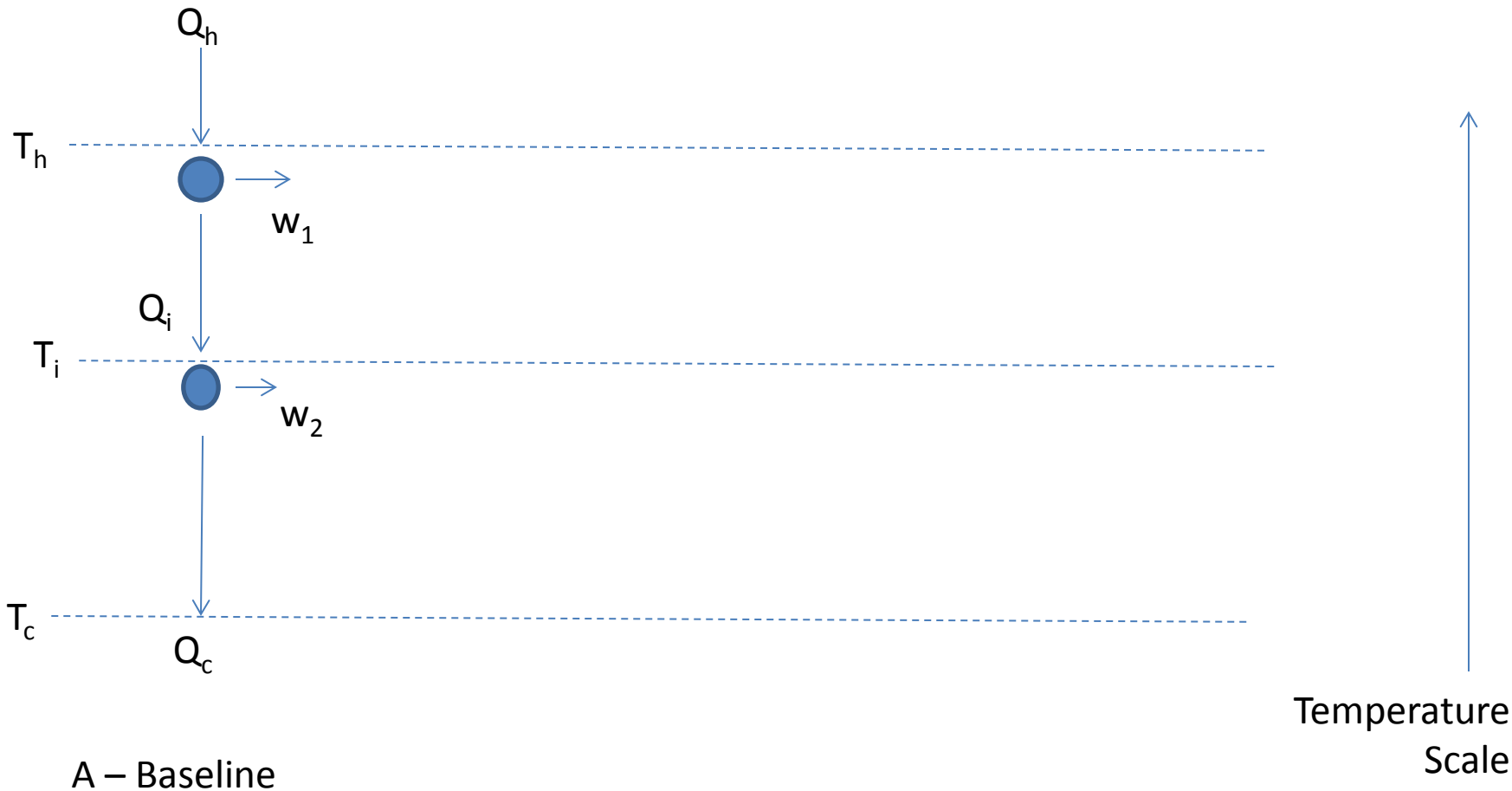
The hot temperature (T_h) reservior delivers heat Q_h to the engine.
Heat Q_c is delivered to the cold temperature (T_c) reservior.
The engine converts part of the heat to work w_1.
Usual thermo relations: $w_1 = Q_h - Q_c$; $Q_h/Q_c = T_h/T_c$.

Thus, the work out depends on the ratio of temperatures.

Description of a two-stage heat engine

In a steam plant, we have at least two turbine stages.

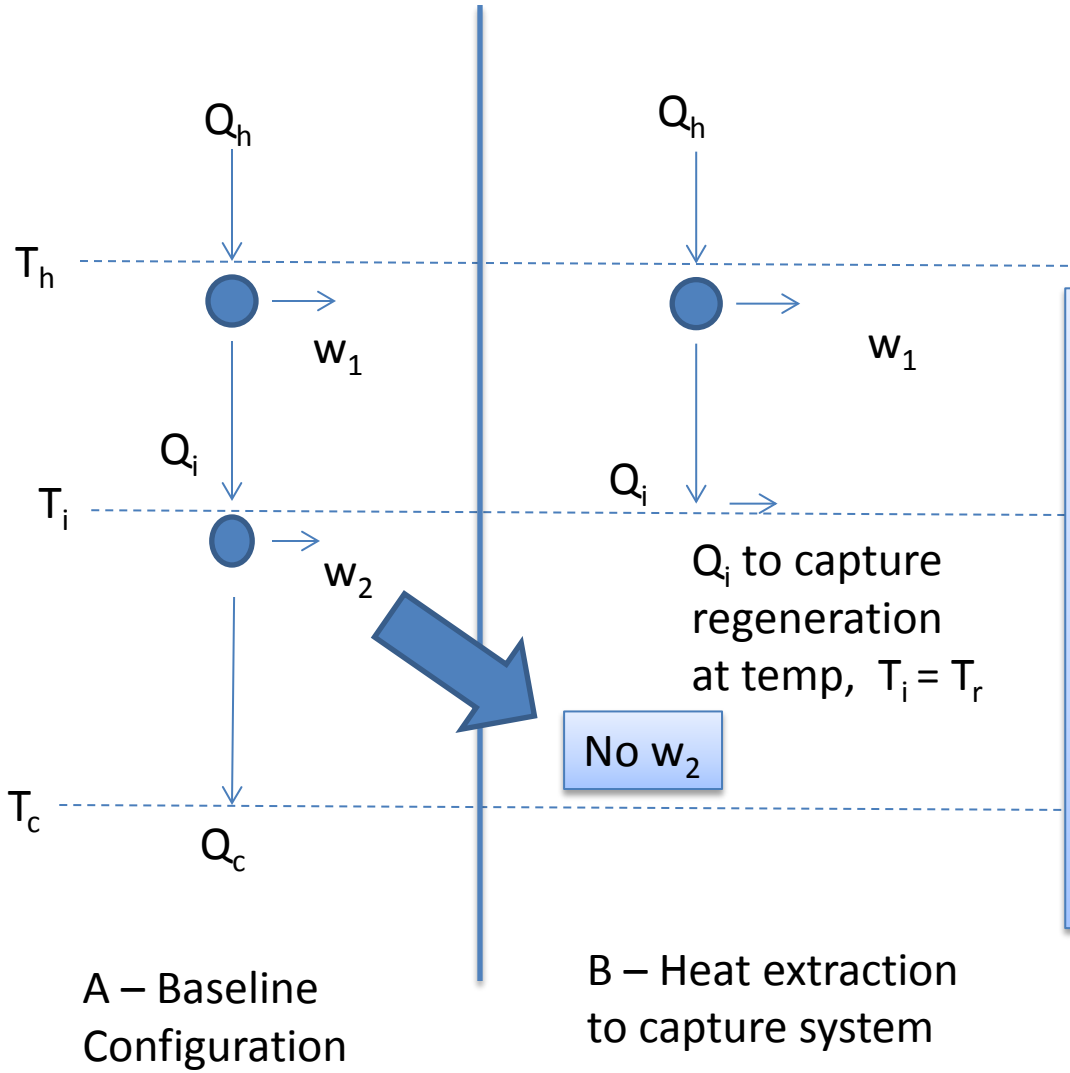
An ideal representation: two heat engines connected by an intermediate temperature T_i



A – Baseline Configuration

Heat for carbon capture regeneration

In a real plant, low-pressure steam extraction is used to regenerate the capture process.
Ideal representation: heat Q_i at temperature T_i used for regeneration at temperature $T_r = T_i$



We need heat at temperature T_i to regenerate the solvent.

We forego w_2 to provide that heat.

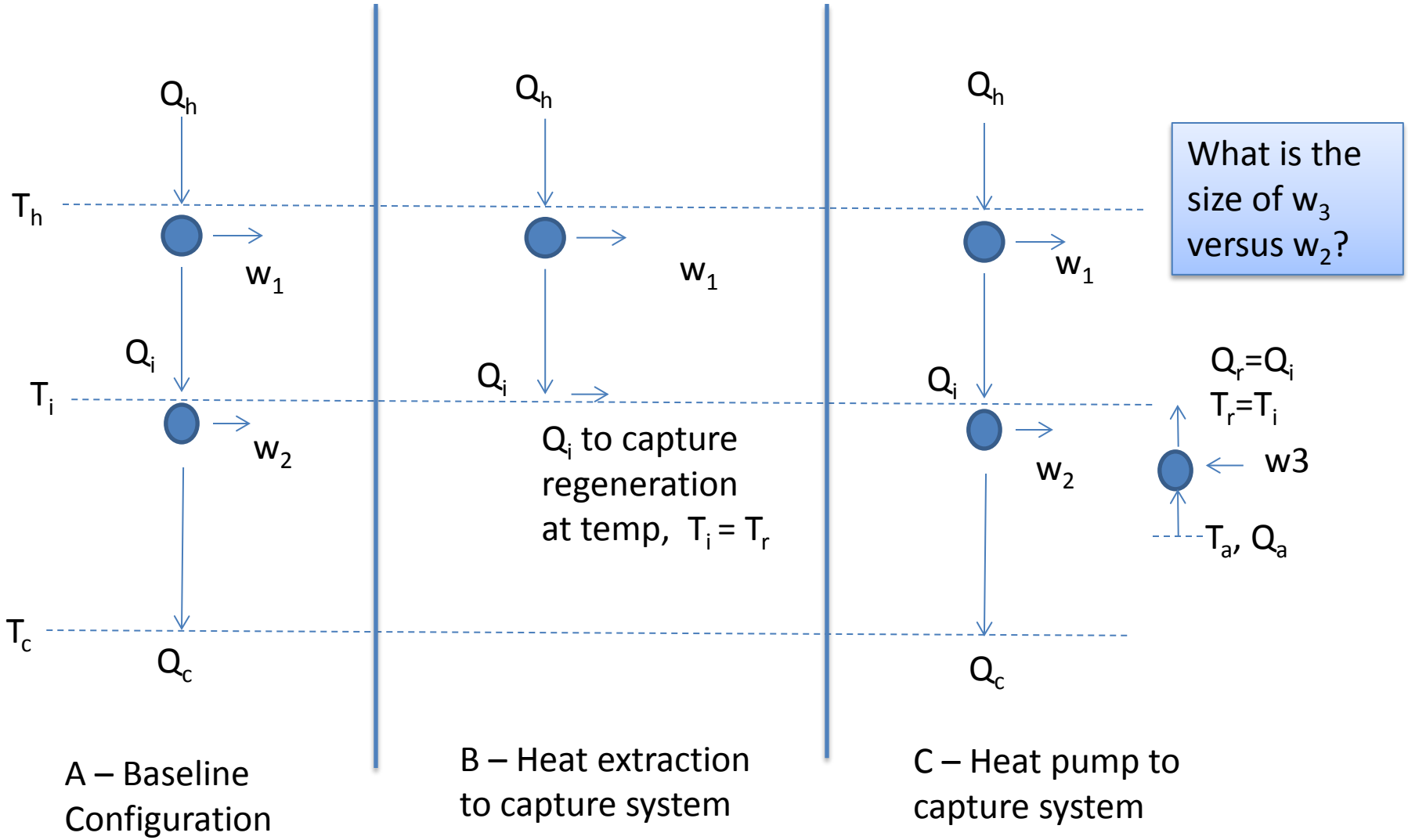
Is there any other supply of heat?

Yes! The absorber must **reject** heat.

But, the rejection temperature is lower than needed to regenerate the solvent.

Heat pump supplying regeneration heat

The engine returns to baseline configuration. Regeneration heat $Q_r = Q_i$ is supplied from a heat pumping from the absorber at temperature T_a. The heat pump needs work W_3 to "upgrade" the absorber heat to the higher temperature.

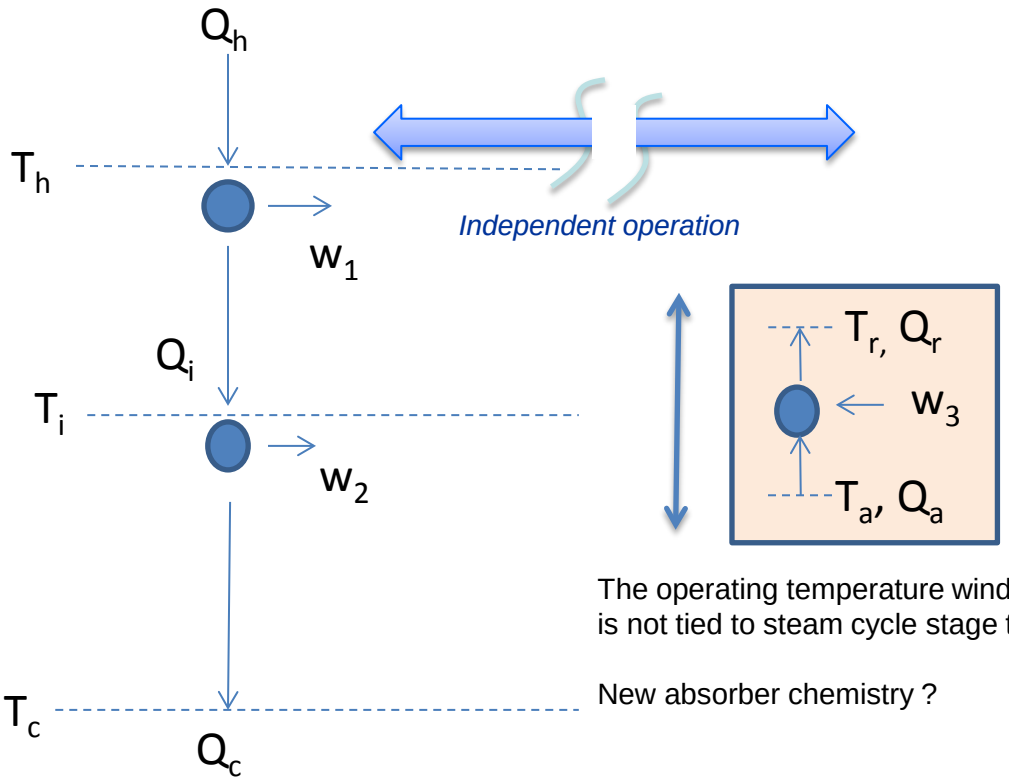


A few comments

- **With a heat pump, you can pick a temperature window. Are there new chemistries for capture?**
- **The heat pump does not affect the power plant operation or configuration – a capture "island".**
- **The heat pump power can come from anywhere.**

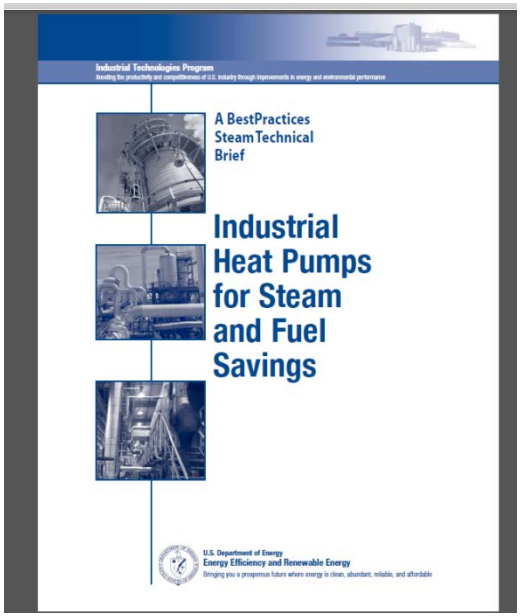
Published systems study:

Kishimoto, A. Kansha, Y, Fushimi, C., Tsutsumi, A. (2011). Exergy Recuperative CO2 Gas Separation in Post-Combustion Capture, Ind. Eng. Chem. Res. 50, pp.10128-10135.



The operating temperature window is not tied to steam cycle stage temperatures.

New absorber chemistry ?



Industrial use of heat pumps is common

Summary

- **Described options for new approaches to generation that span the temperature spectrum:**
  - Oxy-fuel allows high-temperature MHD; makes oxy-fuel an advantage.
  - Pressure gain combustion can produce a step-change efficiency for mid-temperature combined cycles.
  - Heat pumps can exploit the low-temperature carbon capture absorption heat.