Coal Energy Conversion via Combustion in Supercritical Aquifer Water:
An Approach to Electric Power Generation without Atmospheric Emissions

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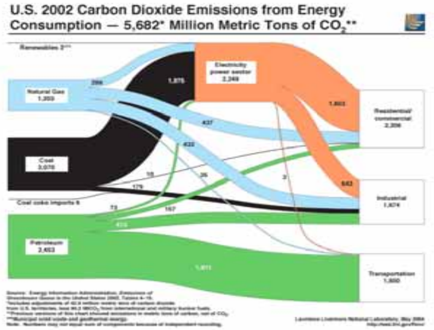
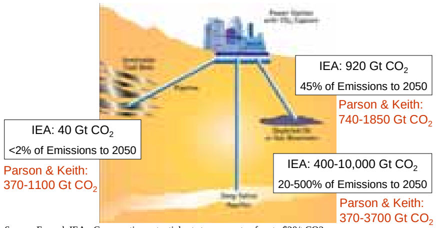
Motivation

Coal is a plentiful, domestic energy resource that accounts for one-half of U.S. electricity generating capacity and one-third of U.S. carbon dioxide emissions. Because of its importance, there is a critical need to find ways to use coal in a more efficient and environmentally sound manner.



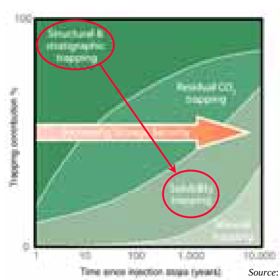
Geologic carbon sequestration has been proposed as a possible solution to enable the continued use of carbon-based fuels. Of the three major options being considered, storage in deep saline aquifers appears to be the most promising based on overall capacity and geographic distribution.



Source: Freund, IEA - Comparative potentials at storage costs of up to \$20/t CO2
Source: Parson & Keith, Science 282, 1053-1054, 1998

Most of today's research into reduced carbon emission energy systems centers around separating a relatively pure stream of CO_2 from either the fuel or the product gases. This stream would then be sent by pipeline to an aquifer for injection.

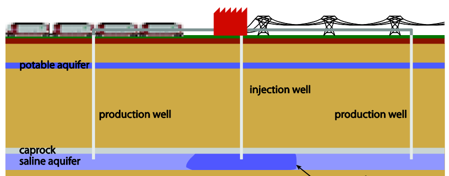
Two disadvantages with this strategy are the significant efficiency loss due to CO_2 separation and the low density of compressed CO_2 compared to aquifer water. Buoyancy would tend to drive the CO_2 back towards the surface through any available route unless trapped by the local geologic structure. This potential for leakage necessitates monitoring to verify permanency of storage. Fortunately, as CO_2 approaches an equilibrium state it dissolves, resulting in a solution more dense than the original aquifer water. Security of aquifer sequestration would be greatly enhanced if the CO_2 was in solution at the time of injection.



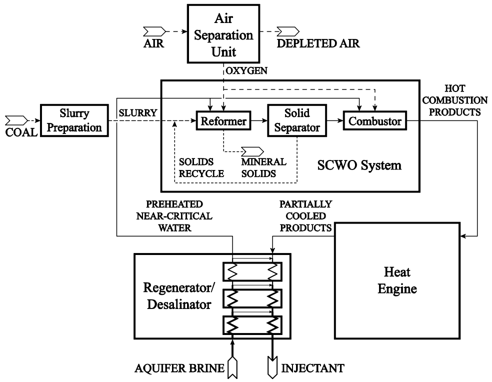
Source: SRCCS 2005, p. 208

System Concept

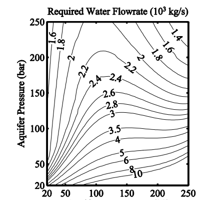
Instead of separating and sequestering CO_2, we propose to combine the energy transformation system with the sequestration medium by using aquifer water as a reaction moderator for the combustion process. Specifically, we consider using supercritical water to reform the coal into a wet supercritical fuel, combusting that fuel in a high-pressure, high-temperature environment suitable for driving a heat engine, and equilibrating the carbonated water to aquifer conditions before re-injection. Our aim is to achieve an efficient method of coal energy conversion that has no matter transfer to the atmosphere and that sequesters the carbon from the coal in the aquifer at near chemical equilibrium—and therefore non-buoyant—conditions.

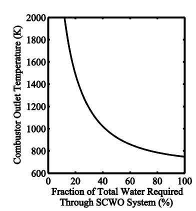


The proposed system consists of an air separation unit (ASU), the supercritical water oxidation (SCWO) system, a regenerator/desalinator, and a heat engine. The ASU provides oxygen for combustion; the low solubility of nitrogen in water precludes the use of air as the oxidizer. The SCWO system consists of a reformer, a solids separator (for inorganic matter), and the combustor. The hot combustion products are used to drive a heat engine, after which they are cooled by regenerative heat exchange before being returned to the aquifer. In the process of heating the aquifer water to the critical point, the salts present in the aquifer water precipitate out of solution and are mechanically separated.



The contour plot below shows the flow rate of water required to dissolve all of the CO_2 produced by a 500 MWe plant. Gas solubility is reduced by the presence of dissolved solids; aquifer salinity is taken as 20,000 ppm w/w NaCl. Not all of this water is required for fuel processing. As shown below right, only a fraction of the water is involved in the combustion process. The remaining water is used for CO_2 dissolution only.

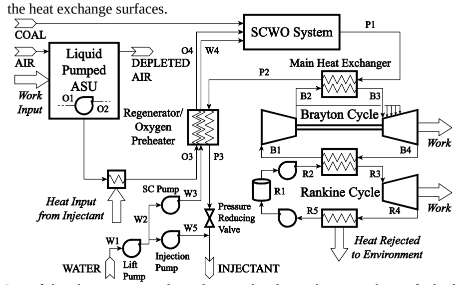




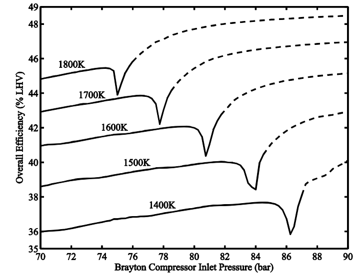
System Analysis

A thermodynamic systems analysis has been performed based on the flow sheet shown below.

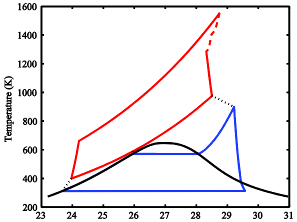
- ASU details are not modeled except for the high pressure liquid oxygen pump (which is not part of a standard cryogenic ASU). The work input requirement is specified according to reported state of the art values.
- Since the internal details of the SCWO system are not required for an equilibrium systems analysis, only its inlet and outlet states are considered. Operating pressure is 250 bar.
- A heat engine configuration consisting of a closed helium Brayton topping cycle and a Rankine bottoming cycle was selected.
  - The first four turbine blade rows are cooled with compressor bleed helium.
  - A pinch point temperature difference of 17K is used in the HRSG.
- The main heat exchanger is pressure matched to ease materials limitations on the heat exchange surfaces.



Most of the plant states are dependent on the above choices and specified inlet conditions. The only remaining independent parameters of the system are the SCWO system outlet temperature (at station P1) and the Brayton cycle compressor inlet pressure (B1). The overall system efficiency is shown below as a function of these two variables.



Due to pressure drops in the SCWO loop, there is a pseudocritical point mismatch in the regenerator, which can result in increased enthalpy leaving with the injectant. This loss causes the troughs in the curves above. The dashed portions represent conditions with SCWO system inlet temperatures (at O4 & W4) below critical. Thus, at a SCWO system outlet temperature of 1600K the conservative optimum choice of Brayton inlet pressure is 79.5 bar. The *T-s* diagram and power balance for this operating condition are shown below.



Component	Power (MW)
Brayton Cycle	
Compressor	-388.4
Turbine	659.9
Net	271.5
Rankine Cycle	
Condensate Pump	-0.026
Feed Pump	-2.27
Turbine	331.6
Net	329.3
ASU	-73.2
Water Pumps	-27.5
Overall Plant	500.0
Firing Rate (LHV basis)	1188.4
Efficiency (% LHV)	42.1%

Current Research

Supercritical Reformer & Solid Separator:

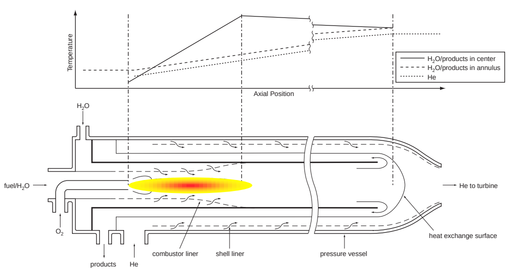
Coal processing is divided into a reformer and combustor so that inorganic solids may be removed at a low temperature. The reformer will deliver a single-phase supercritical water solution of synthesis fuel to the combustor.

Work on this component is being performed by B.J. Kim and colleagues in the group of Professor R.E. Mitchell.

Supercritical Combustor:

The supercritical combustor accepts the synthesis fuel solution from the reformer, brings it to chemical equilibrium, and delivers the products at high temperature for use by the heat engine. Our approach follows a gas turbine based design paradigm wherein fluid mechanics is used to achieve reaction stabilization, overall fluid mixing, and control of hot product interactions with the liner wall.

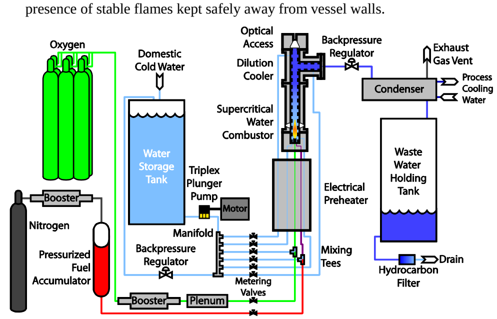
Shown below is a concept schematic of a combustor, including integration of the requisite heat exchange surface with the helium working fluid of the Brayton topping cycle.



Combustion in supercritical water has been studied since the 1970s for hazardous waste destruction, but most of this work has focused on relatively cool and low intensity oxidation. For use in an electric power plant, supercritical water combustion should have the following characteristics:

- Stable, attached flames for continuous, controllable operation
- Unity equivalence ratio, since both fuel and oxygen (from an ASU) have significant cost
- High volumetric firing rate to limit equipment size and capital cost
- Combustor outlet temperature as high as materials will allow for maximum heat engine efficiency

A schematic of a lab scale (50 kWt), continuous flow supercritical water combustor now under construction appears below. Systems for handling liquid fuel, oxygen, water, and exhaust are shown. The combustor will be optically accessible so that direct photography may be used to confirm the presence of stable flames kept safely away from vessel walls.



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