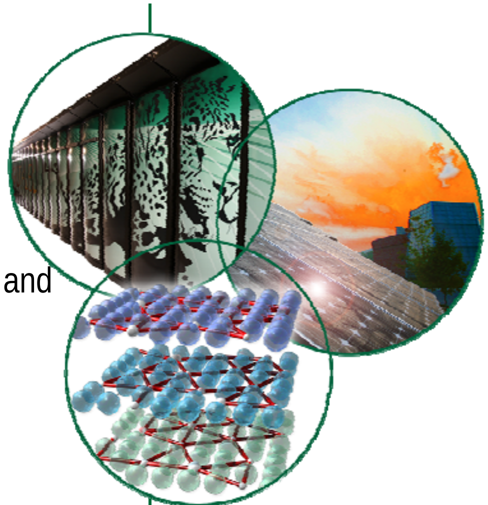
Assessment of Strategies Proposed to Reduce CO_2 Emissions



Costas Tsouris, Doug Aaron, Kevin Ye, Andrew Chung, and Kent Williams

Oak Ridge National Laboratory and

Georgia Institute of Technology

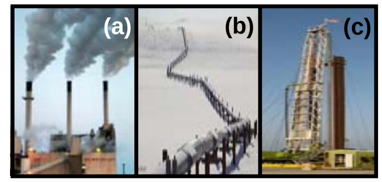
CO_2 Summit
Vail, Colorado, June 9, 2010

Georgia Institute of Technology

Oak Ridge National Laboratory
Managed by UT-Battelle for the Department of Energy

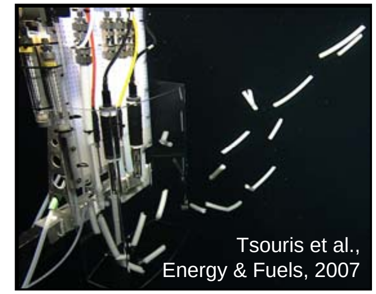
CCS Depends on a Suite of Technologies

- **Separation**[1]
  - Absorption, adsorption, membranes
- **Transportation**
  - Transportation via pipelines (the most viable option)
- **Storage**
  - Storage in aquifers, deep ocean, oil fields, coal seams



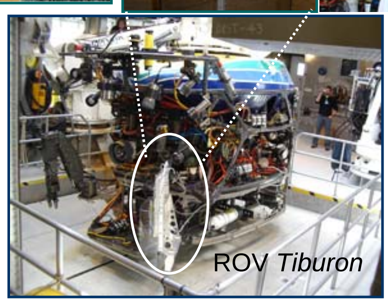
CO_2 is captured (a), transported (b) and stored (c)

Statoil Sleipner facility: stores CO_2 in an aquifer below the North Sea



[1]Aaron and Tsouris, SS&T, 2005

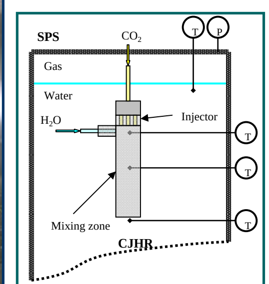
CO_2 Ocean Injection at Monterey Bay, CA

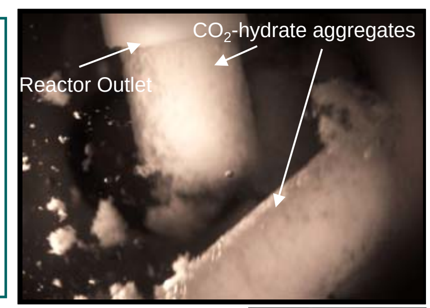


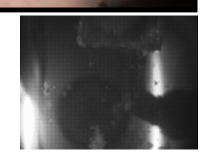
Tsouris et al, ES&T, 2004

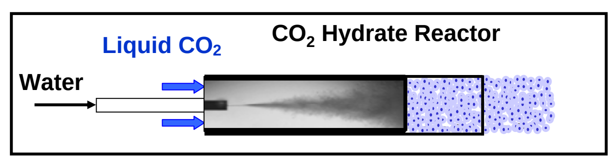
Tsouris et al, Energy & Fuels, 2007

The Hydrate Reactor was Developed at ORNL





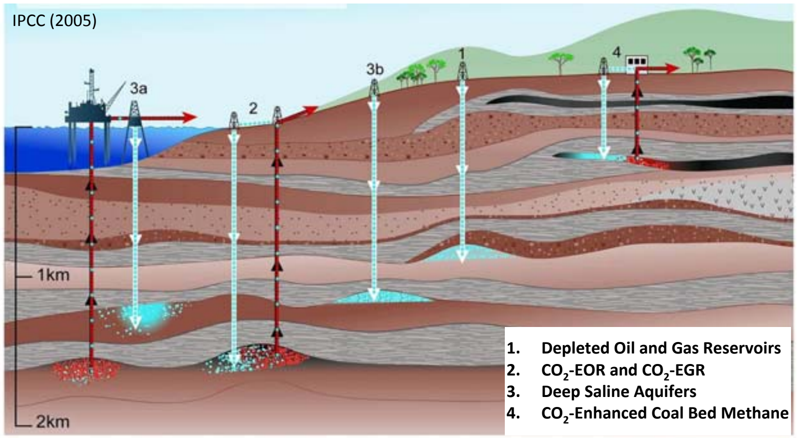




$$CO_{2(l)} + n\,H_2O_{(l)} \leftrightarrow CO_2 \cdot nH_2O_{(s)}$$

Tsouris et al., AIChE J., (2007)

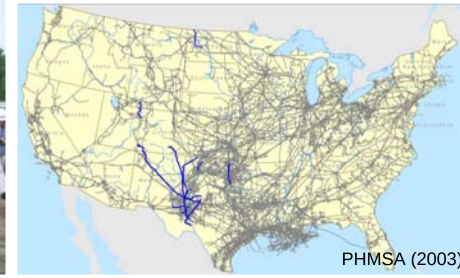
There are Various Options for CO_2 Geologic Storage



CO_2 Transportation is a Mature Technology

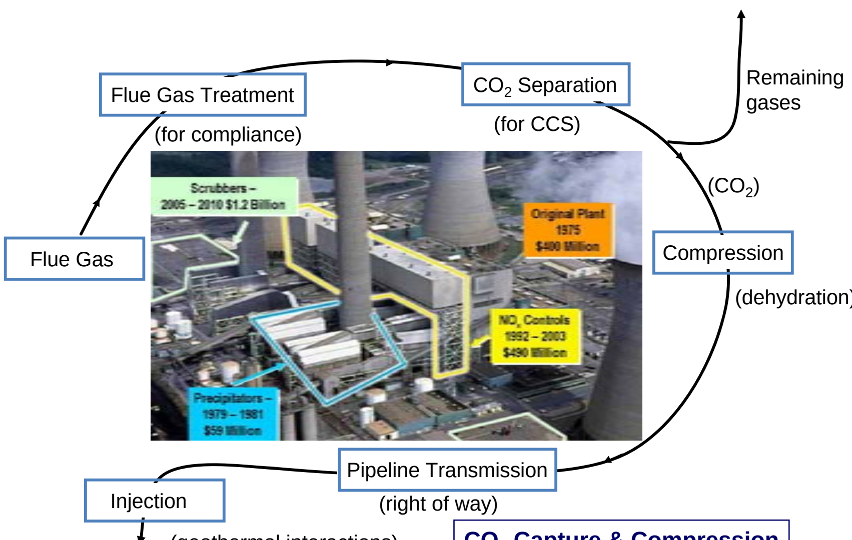
Construction of Green Pipeline, Denbury Resources
Baton Rouge, LA. May, 2009.

~3,500 Miles of CO_2 pipelines transport
~30MtCO_2 per year for EOR activities



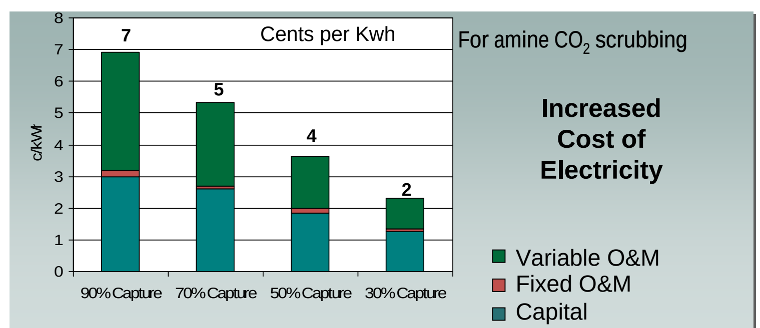
Bielicki, ORNL, 2009

CO_2 Capture is the Biggest Challenge to CCS



CO_2 Capture & Compression
- $1.5 billion capital

The Cost of CO_2 Capture Varies with Capture Efficiency

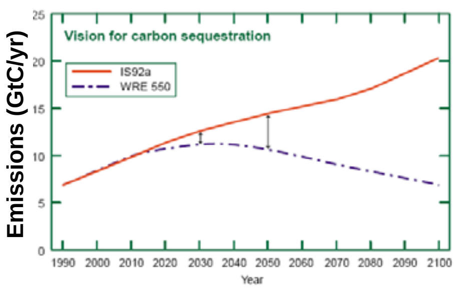


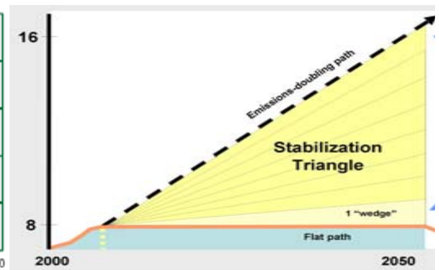
Expect a significant cost for CO_2 capture and compression

Ciferno, 2008

Virtual CCS: A New Concept

- Calculated the resources needed for CCS to stabilize CO_2 emissions
- Used this "pool" of money to build, maintain, operate, and decommission alternative energy installations (Virtual CCS)
- Based calculations on the Pacala and Socolow (2004) eight-wedge stabilization triangle





800 $GtCO_2$ must be avoided over 50 years!

Model Input Data for Comparison of CCS with Wind, Nuclear, and Geothermal Power

- Data taken from the literature determine the scale of CCS and alternative solutions:

CO_2 emissions in 2010	CO_2 emissions increase	Cost of CCS[1]
(GT)	(GT/year)	(\$/ton CO_2)
30	0.64	51

- These data lead to a total, one-wedge cost of \$5.1 trillion over a period of 50 years
- Cost and revenue data for wind and nuclear energy:

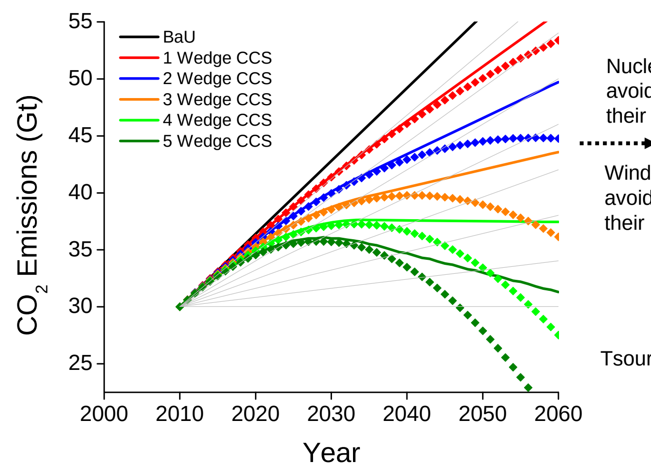
Geothermal installed cost	Geothermal revenue	Nuclear installed cost[2]	Nuclear revenue	Wind installed cost	Wind revenue
(\$/kW)	(\$/kW-yr)	(\$/kW)	(\$/kW-yr)	(\$/kW)	(\$/kW-yr)
2778	438	5046	433	5700	390

[1]IPCC Report [2]Waste disposal cost included

Additional Data Used in the Model

- Capacity factor affects role of renewable energy:
  - Capacity factor:
    - 90% for nuclear - baseload
    - 90% for geothermal - baseload
    - 30% for wind - peak
  - Nuclear and geothermal are easily integrated to the current grid system
- Following the scenario of Pacala and Socolow:
  - Assume CCS lasts from 2010 to 2060 (50 years)
  - Goal is to stabilize CO_2 emissions at 2010 level, thus avoiding all increased emissions

Wind and Nuclear Power Avoid More Carbon Dioxide Emissions than CCS



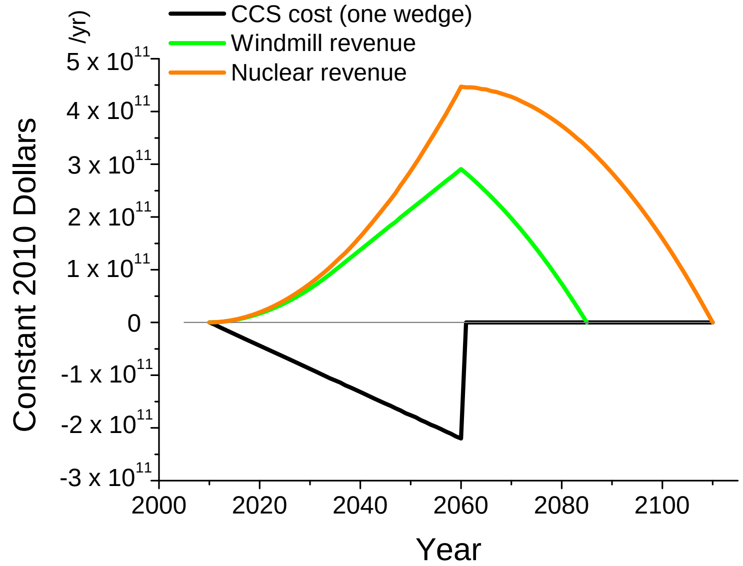
Nuclear plants continue to avoid CO_2 emissions for their 50-years of lifetime

Windmills continue to avoid CO_2 emissions for their 25-years of lifetime

Tsouris et al., ES&T, 2010

- For a 25-year lifetime, windmills avoid 1.9 times more CO_2 than CCS per dollar in overall investment (capital plus operation).
- For a 50-year lifetime, nuclear power plants can avoid 4.3 times more CO_2 than CCS per dollar in overall investment (capital plus operation).

Alternative Energy Generates Revenue



Tsouris et al., ES&T, 2010

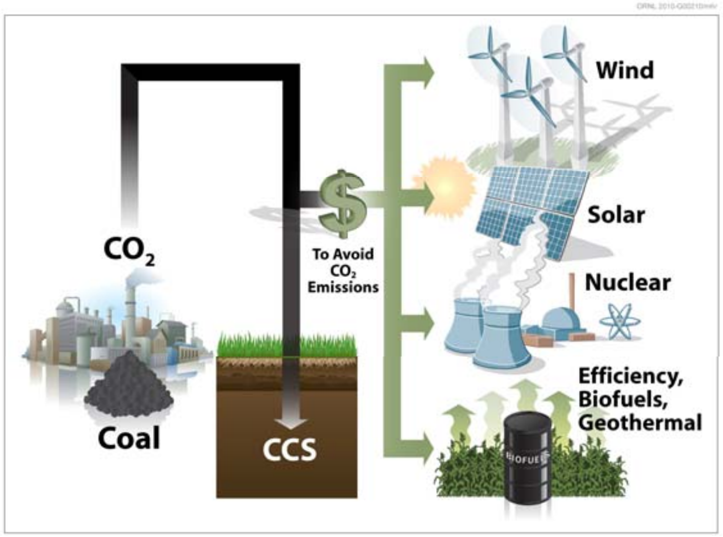
Comparison of CCS and Alternative Energy Shows Alternatives are Better Options

CO_2 avoidance and revenue for a $5.1 trillion investment (1 wedge*)

Technology	Carbon avoidance ratio	Revenue ($)
CCS	1	–
Wind	1.91	9.1 T
Nuclear	4.31	22 T
Geothermal	4.50	27 T

***1 wedge = 100 GtCO_2 avoided over 50 years**

Virtual CCS Can Help Reduce CO_2 Emissions More Effectively than CCS



Tsouris et al., ES&T, 2010

We Can More Effectively Stabilize the CO_2 Concentration in the Atmosphere by:

- Continuing CCS applications that generate revenue (i.e., EOR)
- Ranking carbon avoidance strategies based on effectiveness ratio over CCS and economic performance
- Pursuing virtual CCS, starting from the most promising energy strategies based on ranking
  - Investing resources planned for CCS into low-CO_2 energy technologies
  - Investing in both baseload and peak energy technologies

Virtual CCS is a more sustainable approach because it reduces carbon emissions more effectively and economically than CCS.