The Cost of CO_2 Capture and Storage

Edward S. Rubin
Department of Engineering and Public Policy
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania

Presentation to the
American Association of Petroleum Geologists Annual Convention
New Orleans, Louisiana
April 13, 2010

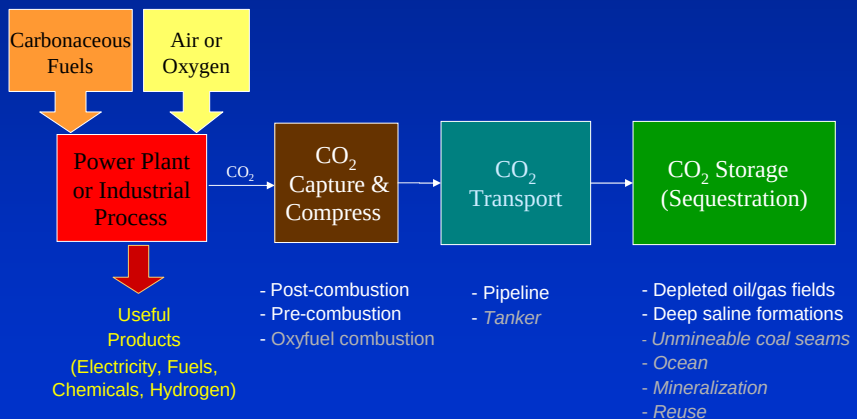
Outline of Talk

- Status of CCS technology
- Current cost estimates
- Potential for cost reductions

Status of CCS technology

E.S. Rubin, Carnegie Mellon

Schematic of a CCS System



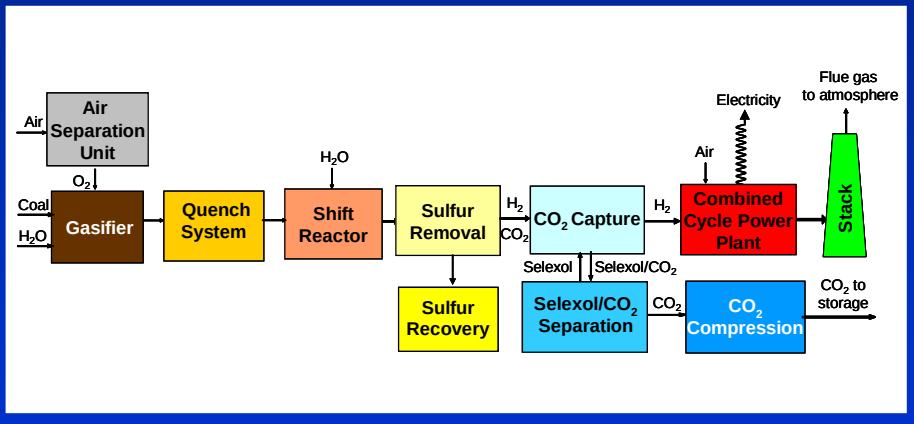
E.S. Rubin, Carnegie Mellon

Leading Candidates for CCS

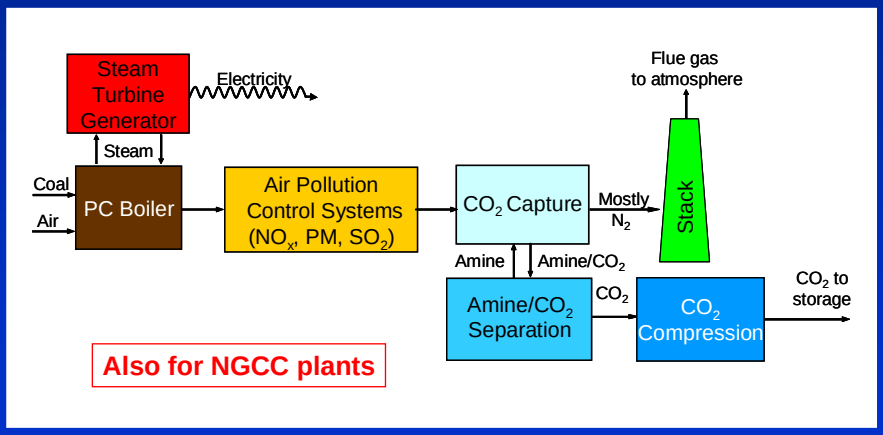
- Fossil fuel power plants
  - Pulverized coal combustion (PC)
  - Natural gas combined cycle (NGCC)
  - Integrated coal gasification combined cycle (IGCC)
- Other large industrial sources of CO_2 such as:
  - Refineries, fuel processing, and petrochemical plants
  - Hydrogen and ammonia production plants
  - Pulp and paper plants
  - Cement plants

– Main focus is on power plants, the dominant source of CO_2 –

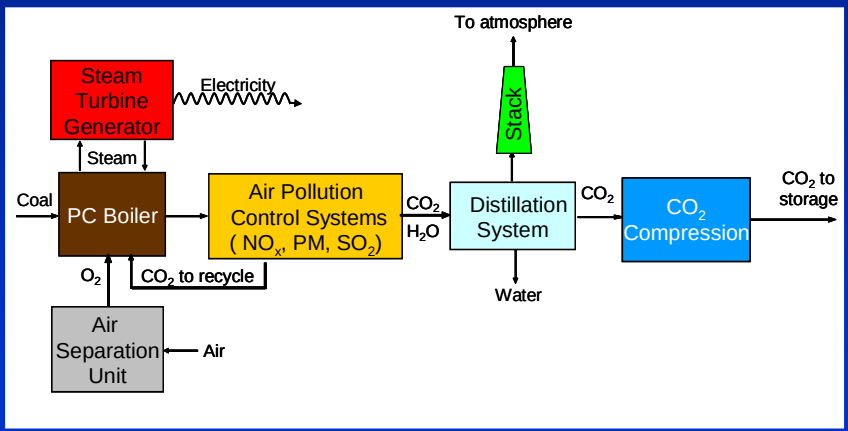
CO_2 Capture Options for Power Plants: Pre-Combustion Capture



CO_2 Capture Options for Power Plants: Post-Combustion Capture



CO_2 Capture Options for Power Plants: Oxy-Combustion Capture



Status of CCS Technology

- Pre- and post-combustion CO_2 capture technologies are commercial and widely used in industrial processes; also at several gas-fired and coal-fired power plants, at small scale (~40 MW); CO_2 capture efficiencies are typically 85-90%. Oxyfuel capture is still under development.
- CO_2 transport via pipelines is a mature technology.
- Geological storage of CO_2 is commercial on a limited basis, mainly for EOR; several projects in deep saline formations are operating at scales of ~1 Mt CO_2 /yr.
- Large-scale integration of CO_2 capture, transport and geological sequestration has been demonstrated at several industrial sites (outside the U.S.) — but not yet at an electric power plant at full-scale.

E.S. Rubin, Carnegie Mellon

Examples of Pre-Combustion CO_2 Capture Systems

(Source: Chevron-Texaco)

Petcoke Gasification to Produce H_2
(Coffeyville, Kansas, USA)

(Source: Dakota Gasification)

Coal Gasification to Produce SNG
(Beulah, North Dakota, USA)

E.S. Rubin, Carnegie Mellon

Pre-Combustion Capture at IGCC Plants

Puertollano IGCC Plant
(Spain)

Source: Elcano, 2007

Pilot plants under construction at two IGCC plants (startup expected in late 2010)

Buggenhum
IGCC Plant
(The Netherlands)

Source: Nuon, 2009

E.S. Rubin, Carnegie Mellon

Post-Combustion Technology for Industrial CO_2 Capture

Source: IEA GHG, 2008

BP Natural Gas Processing Plant
(In Salah, Algeria)

E.S. Rubin, Carnegie Mellon

Post-Combustion CO_2 Capture at U.S. Power Plants

(Source: Flour Daniel)

Bellingham Cogeneration Plant
(Bellingham, Massachusetts, USA)

(Source: IEA GHG)

Warrior Run Power Plant
(Cumberland, Maryland, USA)

E.S. Rubin, Carnegie Mellon

Oxy-Combustion CO_2 Capture from a Coal-Fired Boiler

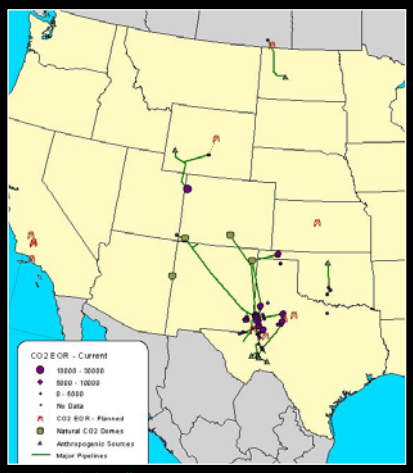
Source: Vattenfall, 2008

30 MW_t Pilot Plant (~10 MW_e) at Vattenfall Schwarze Pumpe Station
(Germany)

E.S. Rubin, Carnegie Mellon

CO_2 Pipelines in the Western U.S.

> 3000 miles of pipeline
~40 $MtCO_2$/yr transported

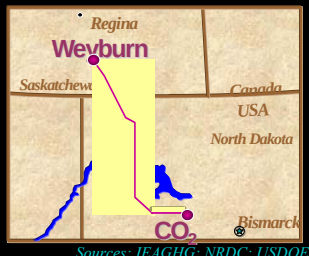


Source: USDOE/Battelle

Source: NRDC

E.S. Rubin, Carnegie Mellon

Geological Storage of Captured CO_2 with Enhanced Oil Recovery (EOR)



Sources: IEAGHG; NRDC; USDOE

E.S. Rubin, Carnegie Mellon

Still Missing

- Full-scale power plant demo #1
- Full-scale power plant demo #2
- Full-scale power plant demo #3
- Full-scale power plant demo #4
- Full-scale power plant demo #5
- Full-scale power plant demo #6
- Full-scale power plant demo #7
- Full-scale power plant demo #8
- Full-scale power plant demo #9
- Full-scale power plant demo #10

The cost of CCS

Many Factors Affect CCS Costs

- Choice of Power Plant and CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; *e.g.*,
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered (CO_2 only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- Time Frame of Interest
  - First-of-a-kind plant vs. n^{th} plant
  - Current technology vs. future systems
  - Consideration of technological "learning"

Common Measures of Cost

- Cost of Electricity (COE) ($/MWh)

$$= \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)$$

- Cost of CO_2 Avoided ($/ton CO_2 avoided)

$$= \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(CO_2/MWh)_{ref} - (CO_2/MWh)_{ccs}}$$

Ten Ways to Reduce Estimated Cost

(inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume EOR credits for CO_2 storage
6. Omit certain capital costs
5. Report \$/ton CO_2 based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume **all of the above !**

. . . and we have not yet considered the CCS technology!

Reminder

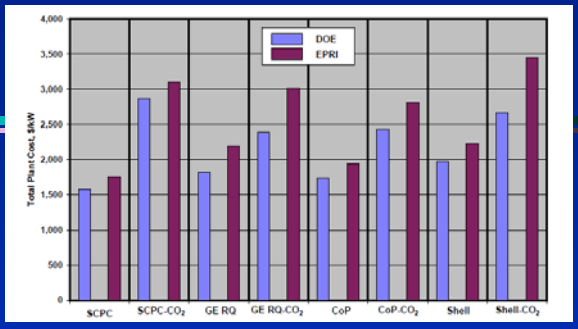
- The *true* costs of CCS are still unknown since we have not yet built and operated full-scale power plants with CCS

Sources of Recent Cost Estimates

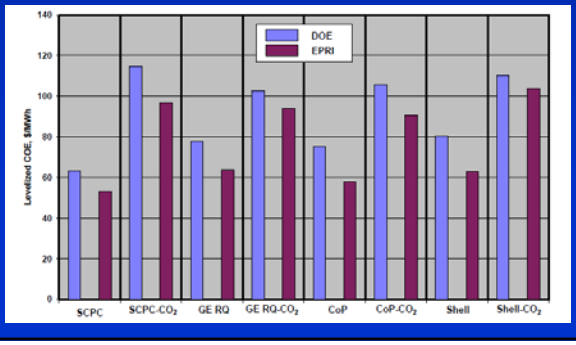
- IPCC, 2005: Special Report on CCS
- Rubin, et.al, 2007: *Energy Policy* paper
- EPRI, 2007: Report No. 1014223
- DOE, 2007: Report DOE/NETL-2007/1281
- EPRI, 2008: Report No. 1018329
- DOE, 2009: Pgh Coal Conference Presentation
- DOE, 2010: Low-Rank Coal Study (forthcoming)

DOE vs. EPRI

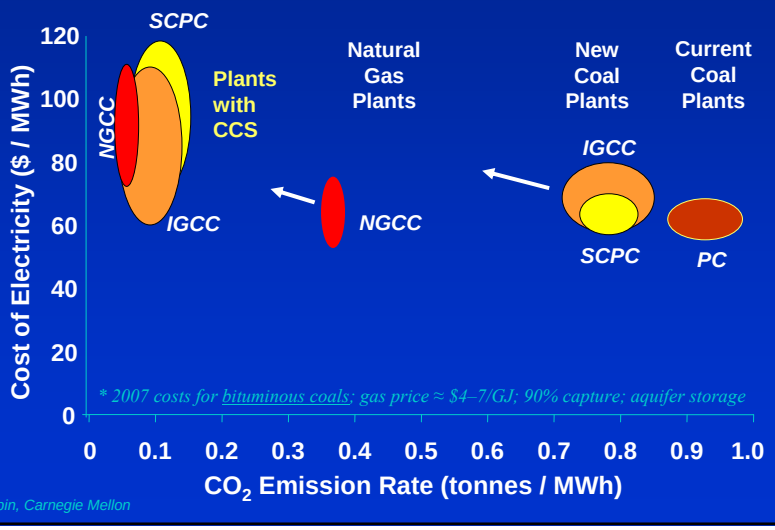
- EPRI's capital costs ($/kW) are higher that DOE's
- EPRI's levelized costs of electricity ($/MWh) are lower than DOE's



Source: EPRI, 2007



Estimated Cost of New Power Plants with and without CCS



E.S. Rubin, Carnegie Mellon

Incremental Cost of CCS for New Power Plants Using Current Technology

Increase in levelized cost for 90% capture

Incremental Cost of CCS *relative to same plant type* without CCS based on bituminous coals	Supercritical Pulverized Coal Plant	Integrated Gasification Combined Cycle Plant
Increases in capital cost ($/kW) and generation cost ($/kWh)	~ 60–80%	~ 30–50%

The added cost to consumers due to CCS will be much smaller, reflecting the number and type of CCS plants in the generation mix at any given time.

E.S. Rubin, Carnegie Mellon

Typical Cost of CO_2 Avoided

(Relative to a SCPC reference plant; bituminous coals)

Levelized cost in US$ per tonne CO_2 avoided

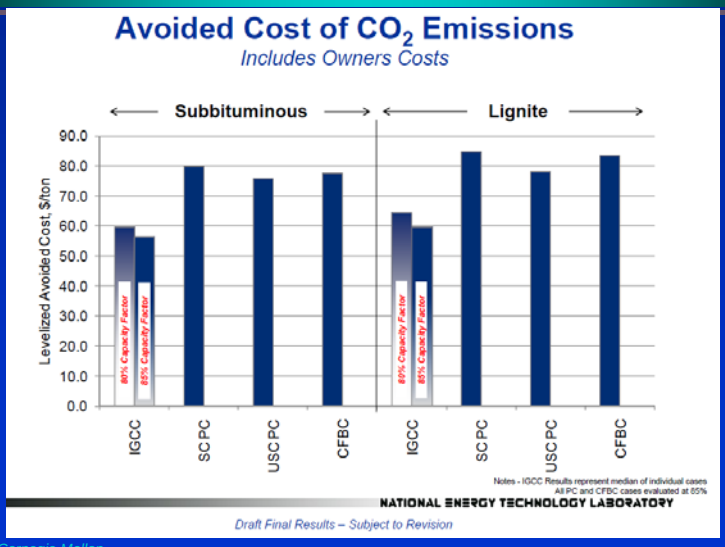
Power Plant System *(relative to a SCPC plant without CCS)*	New Supercritical Pulverized Coal Plant	New Integrated Gasification Combined Cycle Plant
Deep aquifer storage	**~ $70 /t$CO_2$** **±$15/t**	**~ $50 /t$CO_2$** **±$10/t**
Enhanced oil recovery (EOR) storage	Cost reduced by ~ $20–30 /t$CO_2$	

Source: Based on IPCC, 2005; Rubin et al, 2007; DOE, 2007

- ***Capture accounts for most (~80%) of the total cost***

E.S. Rubin, Carnegie Mellon

DOE Cost Results for Low-Rank Coals at Western Power Plants



Source: NETL, 2009

E.S. Rubin, Carnegie Mellon

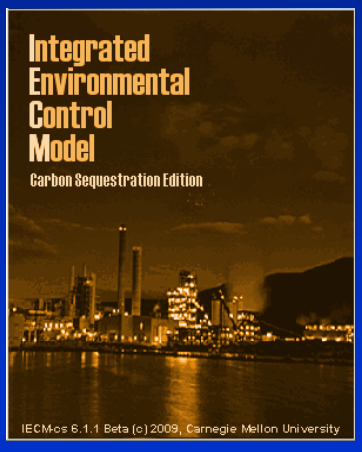
High capture energy requirements is a major factor in high CCS costs

Power Plant Type	Added fuel input (%) per net kWh output
Existing subcritical PC	~40%
New supercritical PC	25-30%
New coal gasification (IGCC)	15-20%
New natural gas (NGCC)	~15%

Changes in plant efficiency due to CCS energy requirements also affect plant-level pollutant emission rates (per MWh). A site-specific context is needed to evaluate the net impacts.

Analyzing Options for Power Plants
(IECM: The Integrated Environmental Control Model)

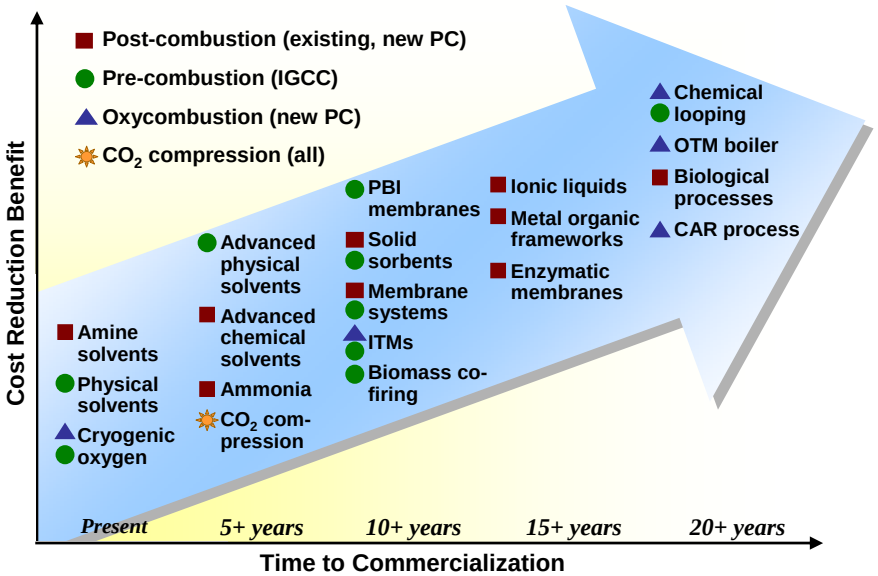
- A desktop/laptop computer model developed for DOE/NETL; free and publicly available at: www.iecm-online.com
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - CO_2 capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
  - Major update in late 2009



What is the potential for future cost reductions?

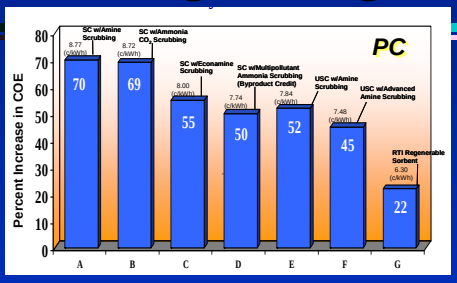
E.S. Rubin, Carnegie Mellon

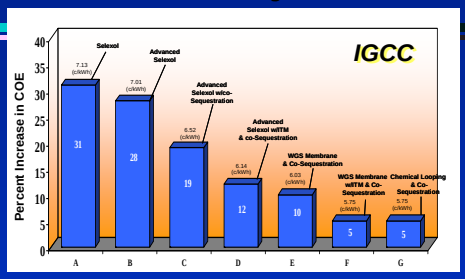
Better Capture Technologies Are Emerging

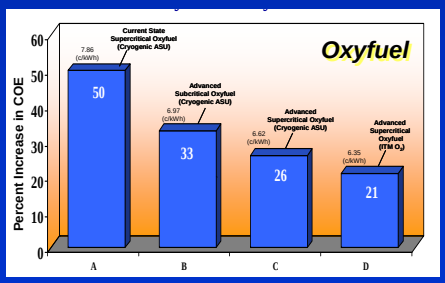


OFFICE OF FOSSIL ENERGY

Potential Cost Reductions Based on Engineering-Economic Analysis





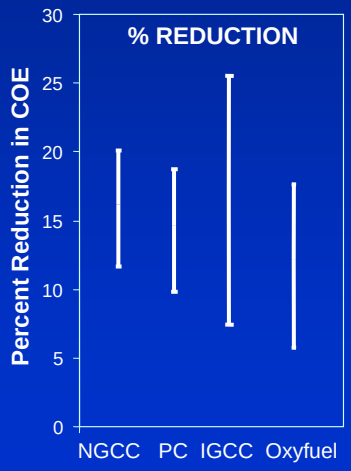


19% -28% reductions in COE w/ CCS

Source: DOE/NETL, 2006

Potential Cost Reductions Based on Learning Curve Analysis *

(after 100 GW of cumulative CCS capacity worldwide)



- **Upper bound of projected cost reduction are similar to estimates from DOE's "bottom-up" analyses**

* Plant-level learning curves developed from component-level analyses for each system

Conclusions

- Significant potential beyond 2020 to reduce the cost of carbon capture via:
  - New or improved CO_2 capture technologies
  - Improved plant efficiency and utilization
- But first need to build and operate some full-size plants with current technology

Thank You

rubin@cmu.edu

E.S. Rubin, Carnegie Mellon