The Government Role in Environmental Technology Innovation

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Innovation for Energy and the Environment (19-688)
Carnegie Mellon University
October 13, 2010

Motivating Questions

• What kinds of technology innovations are needed to mitigate greenhouse gas emissions?
• What do we know about the process of technology innovation?
• How do government actions influence technology innovation?
• What types of policies are needed to stimulate innovations that mitigate climate change?

Sources of U.S. CO₂ Emissions

Electricity generation and vehicles together account for nearly 75% of U.S. CO₂ emissions—burning coal and oil are the two main sources.
Technology Innovations Needed to Mitigate CO₂ Emissions

- More efficient technologies for energy conversion and utilization
- Technologies to produce and utilize alternative energy sources with lower or no GHG emissions
- Technologies for CO₂ capture and storage at large stationary sources
- Technologies that reduce the demand for energy-intensive goods and services

Scale of Deployment Needed

- To achieve significant CO₂ emission reductions, the U.S. alone will have to retrofit or replace:
  - Hundreds of power plants
  - Tens of millions of automobiles/yr
  - Hundreds of millions of other end-use devices

Requires deployment of new technology on a massive scale... This won’t happen overnight!

What do we know about the process of technology innovation?

Elements of Technological Change

- Invention
  - Discovery; creation of knowledge; new prototypes
- Innovation
  - Creation of a commercial product or process
- Adoption
  - Deployment and use of the new technology
- Diffusion
  - Increasing adoption and use of the technology
Challenge 1: Accelerate the Pace of Innovation

The Linear Model of Technological Change

Invention → Innovation → Adoption → Diffusion

A More Realistic Model

Invention → Innovation → Adoption → Diffusion

R&D Learning By Doing Learning By Using

U.S. “Technology Policy” Tools

How do government actions influence technology innovation?

Direct Government Funding of Research and Development (R&D)
- R&D contracts with private firms
- R&D grants and contracts with universities
- Intramural R&D conducted at gov’t laboratories
- R&D contracts with consortia (2 or more of the actors above)

Direct or Indirect Support for Commercialization and Production; Indirect Support for Development
- Patent protection
- R&D tax credits
- Production subsidies or tax credits to firms bringing new technologies to market
- Tax credits or rebates for new technology buyers
- Government procurement
- Demonstration projects

Support for Learning and Diffusion of Knowledge and Technology
- Education and training
- Codification and transfer of knowledge
- Technical standard-setting (non-regulatory)
- Technology and/or industrial extension services
- Publicity and consumer information

* These policies influence different phases of the innovation process
* Provide “carrots” to incentivize technological change & innovation
Technology Policies Have Reduced the Cost of GHG-Friendly Energy Systems

Lessons Learned from Study of U.S. Technology Policies

• To realize the benefits of technology innovation, a balanced policy portfolio must support not only R&D, but also promote technology deployment and diffusion of knowledge.
• Technology innovations cannot be planned or programmed; because outcomes are uncertain, policies should support a suite of options and approaches rather than a specific technology or design.
• Gov’t support for education and training, as well as research, enhances the infrastructure necessary to support innovation.
• Competition among gov’t programs (as well as R&D performers) contributes to innovation by encouraging diverse approaches.
• Effective policies and programs require insulation from short-term political pressures that impede steady progress that is critical to long-term innovations.

What About Environmental Technologies?

• Most research on innovation has focused on technology policies in a market economy.
• Relatively little study of gov’t. role in innovation for “environmental technologies” whose sole purpose is to achieve environmental goals.
• Retrospective case studies can provide useful insights.
• At Carnegie Mellon we have conducted case studies of:
  • Power plant air pollution control technologies (SO₂ and NOₓ).
  • Automotive air pollution control systems (CO, HC, NOₓ).
  • CO₂ capture and storage technologies.
  • A variety of energy systems and industrial processes relevant to climate change mitigation.

Research Methods

• Analysis of Regulations & Standards.
• Analysis of Patents Filed in the U.S.
• Analysis of Technological “Learning.”
• Analysis of R&D Expenditures.
• Analysis of Major Conference Activities.
• Detailed Interviews with Key Experts.
Results for Power Plant

SO₂ Control Technology

U.S. Government Actions Affecting SO₂ Control Technology

• Legislation / Regulation
  – New Source Performance Standards of 1971, 1979
  – Stringent SO₂ reductions for new and existing sources
  – SO₂ capture technology required for new plants since 1979

• R&D Funding / Financial Incentives
  – EPA multi-million $ research budget in 1970s
  – DOE Clean Coal Technology Program (since 1985)

• Facilitating Technology Transfer
  – SO₂ Control Symposia (since 1969)
  – Other conferences, workshops, etc

Emission Reduction Options

• Reduce (or shut down) production
• Switch to a cleaner fuel
• Switch to a cleaner production process
• Install emission control technology
• Trade emission allowances (after 1990)

Technologies for SO₂ Control

• Low to Moderate Removal Efficiency
  • Coal cleaning
    • Sorbent injection systems
• High Removal Efficiency
  • Flue gas desulfurization (FGD) systems
  • Combined pollutant removal systems
Data Contained in a Patent

**United States Patent**

**Inventors:**
- E.S. Rubin, Carnegie Mellon

**Patent Number:** 4,279,873

**Filed:** Jul. 21, 1980

**Title:** Process for Flue Gas Desulfurization

**Applicant:**
- E.S. Rubin, Carnegie Mellon

**Assignee:**
- A. N. Nire Aminlate, Solvay

**Application No.:** 26,282

**Filed:** May 17, 1980

**Foreign Patent Documents:**
- **C/N:** US 4,281,538
  - **Country:** Canada
  - **Date:** 11/09/80

**Field of Search:**
- 421-GM 487 264 342 242

**References Cited:**
- 8 US PATENT DOCUMENTS
  - 3,841,961 11/1974
  - 3,624,648 10/1971
  - 3,652,841 8/1972
  - 3,654,308 8/1972
  - 3,658,374 8/1972
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  - 3,687,519 7/1972
  - 3,687,520 7/1972
  - 3,687,521 7/1972
  - 3,687,522 7/1972
  - 3,722,276 1/1973

**Inventors:**
- E. S. Rubin, A. N. Nire

**Assignee:**
- Aminlate, Solvay

**Application No.:** 26,282

**Filed:** May 17, 1980

**Primary Classification:**
- D01F 5/114

**Abstract:**

This is a method for desulfurization of flue gas from a flue gas desulfurization system. The flue gas is passed through a reaction zone for oxidation of sulfides. The sulfides are then converted to sulfuric acid and the resulting aerosols are captured and collected. The collected aerosols are then converted to sulfuric acid and then collected.

**U.S. Patenting Activity in SO2 Control Technology**

**Insights from Patent Analysis**

- Historical trends in inventive activity and their relation to key government actions
- Identify categories and types of environmental technology innovations
- Identify sources of inventive activity
  - By performer (e.g., industry, govt’., etc.)
  - By nation of origin

**Patents in Pre-Combustion Control**

(Abstract-based dataset)
Adoption of FGD Technology (Coal-Fired Power Plants)

Schematic of a Power Plant SO₂ Removal System

Atop an SO₂ Absorber
Learning (Experience) Curves

General equation:

\[ y_i = a x_i^{-b} \]

where,

- \( y_i \) = time or cost to produce \( i \)th unit
- \( x_i \) = cumulative production thru period \( i \)
- \( b \) = learning rate exponent thru period \( i \)
- \( a \) = coefficient (constant)

Percent cost reduction for a doubling of cumulative output is often used as a measure of learning rate.

Historical “Learning Curve” for Flue Gas DeSOx Technology

Cost reduction = 11% per doubling of installed capacity; 50% reduction over 20 years.

Initial cost estimates were a bit optimistic (O&M costs also low).

Early Trend of FGD Capital Cost
Results for Power Plant

NO\textsubscript{x} Control Technology

Technologies for NO\textsubscript{x} Control

- Low to Moderate Removal Efficiency
  - Low-NO\textsubscript{x} burners
  - Other combustion modifications
  - Non-selective catalytic reduction (SNCR)
- High Removal Efficiency
  - Selective catalytic reduction (SCR)
  - Combined pollutant removal systems

U.S. Government Actions Affecting NO\textsubscript{x} Control Technology

- CAA Legislation / Regulation
  - Ozone Transport Commission and EPA SIP-Call, 1990s
- Low to moderate reductions for new sources since 1971; stringent standards since 1997
- Some reductions at existing gas-fired plants since 1970s; no significant reductions for existing coal-fired plants until mid-1990s

Inventive Activity in NO\textsubscript{x} Control

(U.S. Patents, Class-based dataset)
Early Trend of SCR Cost Estimates

- First German commercial installation on a coal-fired power plant.
- First German commercial installation.
- First US commercial installation.

Cumulative World SCR Installed Capacity (GW)

- Control Technology
- Early O&M costs also low


- Stigied limits: HC, NOx, CO
- Year vs HC

Technological Evolution of Emission Control Systems

- Thermal Management System
- Three-Way Catalysts
- Oxidation Catalysts
- Catalysis

Results for Automotive Emissions Control Technology
U.S. Patenting Activity in Automotive Emission Controls

Estimated Cost of Automotive Emission Control System

Estimated Emissions Control Cost Excluding Cost of Precious Metals

Emission Control Cost as Percent of Average Vehicle Cost
Conclusions from Case Studies

- The stringency of emission reduction requirements is a major factor in both stimulating and directing inventive activities and the deployment of cleaner technologies.
- The cost of achieving a given level of emissions reduction tends to fall with increasing deployment and sustained R&D.
- Estimated learning rates are similar to those for other consumer technologies in the marketplace.
- No strong empirical basis for comparing alternative environmental policy instruments.

Implications for CO₂ Capture Technology

Focus on Carbon Capture and Sequestration Technologies

- CO₂ capture and sequestration (CCS) is a relatively new carbon management option that could allow continued use of fossil fuels with no/low atmospheric emissions of CO₂.
- Most attractive applications are for large-scale power generation and synfuels production.
- CO₂ capture technology now used in industrial processes and a few power plants (at small scale).
- Large-scale geologic sequestration now being demonstrated in the Norway, Algeria and Canada; more planned demos in the U.S. and elsewhere.
Study Approach

- Quantify historical learning rates of energy and environmental technologies relevant to power plants with CO₂ capture
- Apply these results to leading plant design options to estimate learning rates and future costs of power plants with CO₂ capture*

* Excludes the costs of CO₂ transport and storage

Retrospective Case Studies

- Flue gas desulfurization systems (FGD)
- Selective catalytic reduction systems (SCR)
- Gas turbine combined cycle system (GTCC)
- Pulverized coal-fired boilers (PC)
- Liquefied natural gas plants (LNG)
- Oxygen production plants (ASU)
- Hydrogen production plants (SMR)

GTCC Capital Costs

- Investment Price USD (1990$/kW)
- Source: Colpier and Cornland (2002)

LNG Plant Capital Costs

- Liquefaction capital cost ($/tpa)
- Actual liquefaction unit cost
- Theoretical liquefaction unit cost
- LNG Production

y = 269x - 0.22
R² = 0.52
PC Boiler Capital Costs

Oxygen Plant Capital Cost

Case Study Learning Rates

Baseline CCS Plant Designs (I)
Baseline CCS Plant Designs (2)

IGCC Plant

Step 1: Disaggregate each plant into major sub-sections

For example:
- IGCC Plant Components
  - Air separation unit
  - Gasifier area
  - Sulfur removal/recovery system
  - CO₂ capture system (WGS+Selexol)
  - CO₂ compression
  - GTCC (power block)
  - Fuel cost

Baseline Plant Characteristics

- Approximately 500 MW net output
- Supercritical PC and Quench gasifier IGCC
- Pittsburgh #8 bituminous coal
- 75% levelized capacity factor
- 14.8% fixed charge factor
- All costs in constant 2002 dollars

Step 2: Estimate current plant costs and contribution of each sub-section

Levelized costs in constant $2002

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>Capital Cost</th>
<th>Annual O&amp;M Cost</th>
<th>Cost of Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant w/ Capture</td>
<td>1,831 $/kW</td>
<td>21.3 $/MWh</td>
<td>62.6 $/MWh</td>
</tr>
<tr>
<td>Air separation unit</td>
<td>18 %</td>
<td>8 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Gasifier area</td>
<td>27 %</td>
<td>17 %</td>
<td>24 %</td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>6 %</td>
<td>3 %</td>
<td>5 %</td>
</tr>
<tr>
<td>CO₂ capture system*</td>
<td>13 %</td>
<td>7 %</td>
<td>11 %</td>
</tr>
<tr>
<td>CO₂ compression</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td>34%</td>
<td>9%</td>
<td>25%</td>
</tr>
<tr>
<td>Fuel cost**</td>
<td>--</td>
<td>54%</td>
<td>19%</td>
</tr>
</tbody>
</table>

*Excludes costs of CO₂ transport and storage  **Based on Pittsburgh #8 coal @ $1.0/GJ
**Step 3:** Select learning rate analogues for each plant component

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>FGD</th>
<th>SCR</th>
<th>GTCC</th>
<th>PC boiler</th>
<th>LNG</th>
<th>O₂ prod</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air separation unit</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasifier area</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ capture system</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ compression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step 4:** Estimate current capacity of major plant components

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>Current MW/Equiv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant Components</td>
<td></td>
</tr>
<tr>
<td>Air separation units</td>
<td>50,000</td>
</tr>
<tr>
<td>Gasifier area</td>
<td>10,000</td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>50,000</td>
</tr>
<tr>
<td>CO₂ capture system</td>
<td>10,000</td>
</tr>
<tr>
<td>CO₂ compression</td>
<td>10,000</td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td>240,000</td>
</tr>
</tbody>
</table>

**Step 5:** Set projection period and start of learning

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Cumulative CCS Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Learning Begins at:</td>
</tr>
<tr>
<td></td>
<td>1st Plant</td>
</tr>
<tr>
<td>NGCC Plant</td>
<td>432</td>
</tr>
<tr>
<td>PC Plant</td>
<td>500</td>
</tr>
<tr>
<td>IGCC Plant</td>
<td>490</td>
</tr>
<tr>
<td>Oxyfuel Plant</td>
<td>500</td>
</tr>
</tbody>
</table>

**Step 6:** Sensitivity Analysis

- Learning starts at either first or nstill plant
- Range of component learning rates
- Projection to 50 GW of worldwide capacity
- Lower estimates of current component capacity
- Effect of additional non-CCS experience
- Higher fuel prices for coal and natural gas
- Lower financing costs + higher plant utilization
Results for IGCC Capital Cost
(Assuming learning begins at first capture plant)

Based on nominal case study assumptions

Summary of Learning Rate Results
(Based on 100 GW of cumulative CCS capacity)

Summary of COE Results
(Based on 100 GW of cumulative CCS capacity)
Conclusions from This Study

- Future costs of power plants with CO₂ capture can be reduced significantly; but …
- Achieving future cost reductions will require not only sustained R&D, but also large-scale deployment to foster learning-by-doing
- IGCC plants have potential for larger cost reductions than combustion-based plants (esp. from economies of scale)
- The timing and magnitude of future cost reductions are uncertain; policy drivers will play a key role

What types of policies are needed to stimulate innovations that mitigate climate change?

Innovation Policies for Climate Change Mitigation

- Global climate change is an environmental problem that cannot be addressed by technology policies alone
- Regulatory policies limiting GHG emissions also are needed to mitigate climate change and achieve the international goal of stabilizing GHG concentrations
- Energy policies can further help—or impede—progress and innovations that reduce GHG emissions
- A combination of regulatory policies and traditional technology policies can most effectively foster innovations favored or required by markets in a carbon-constrained world

Thanks!

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