Experience Curves for Environmental Technology and Their Relationship to Government Actions

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Electric Utilities Environmental Conference
Tucson, Arizona
January 28, 2003
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Motivation

• The cost of technology to control emissions of harmful substances has been a key factor in the development of regulations and standards governing air pollution emissions from electric power plants.

• Today, power plant emissions of CO₂ are again the subject of intense study in the context of global climate change.

• Historical experience in controlling other major pollutants may offer some guidance as to how the cost of new environmental control requirements might evolve in the future.
Project Goals and Approach

• Elucidate government role in environmental technology innovation and diffusion

• Focus on major environmental technologies already in use at electric power plants with relevance to CO$_2$ capture technology:
  - SO$_2$ control
  - NO$_x$ control

• Quantify rates of technical change for these systems based on historical experience

• Use these empirical results to study potential role of carbon capture and sequestration (in collaboration with IIASA and others)
Results for $SO_2$ Control Technology
U.S. Government Actions Affecting SO$_2$ Control Technology

- **Legislation / Regulation**
  - New Source Performance Standards of 1971, 1979
  - Stringent SO$_2$ reductions for new and existing sources
  - SO$_2$ 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**
  - SO$_2$ Control Symposia (since 1969)
  - Other conferences, workshops, etc
Inventive Activity in SO$_2$ Control
(U.S. Patents, Class-based dataset)
Adoption of FGD Technology
(Coal-Fired Power Plants)

The chart illustrates the cumulative capacity of Wet FGD systems (GWe) across different countries from 1972 to 1998. The chart highlights the adoption rates of FGD systems in various countries, including the US, Japan, Germany, and other countries.

- **US**: Demonstrates a steady increase in capacity from 1972 to 1998, showing rapid growth after 1982.
- **Japan**: Shows a gradual increase in capacity, starting from a lower base than the US.
- **Germany**: Exhibits a moderate adoption rate, beginning with a small capacity in 1972.
- **Other**: Reflects a diverse adoption pattern, with varying capacities throughout the years.

The graph extends from 1972 to 1998, with a clear trend towards increased capacity in all regions by 1998.
Trend in FGD Capital Cost
(500 MW coal plant, 3.5%S coal, 90% SO₂ removal)
Trend in FGD O&M Costs
(500 MW coal plant, 3.5%S coal, 90% SO₂ removal, 65% CF)
Learning (Experience) Curves

General equation:

\[ y_i = ax_i^{-b} \]

where,

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

Percent cost reduction for a doubling of cumulative output is often used as a measure of learning rate
Why Might Cost of Production Decline?

- Changes in production
  - process innovations, learning effects and economies of scale.
- Changes in the product itself
  - product innovations, product redesign, and product standardization.
- Changes in input prices
  - Experience curves typically aggregate all of these factors.
Normalized Experience Curve for FGD Capital Cost

Cost reduction = 11% per doubling of installed capacity

Cumulative World Capacity of Wet FGD Systems (GWe)

(Based on 90% SO₂ removal, 500 MW plant, 3.5% coal)
Results for NO$_x$ Control Technology
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** \textit{new sources} **since 1971; stringent standards since 1997**

- **Some reductions at existing** \textit{gas-fired} **plants since 1970s; no significant reductions for existing** \textit{coal-fired} **plants until mid-1990s**
Adoption of SCR Technology
(Coal-Fired Power Plants)
Trend in SCR Capital Cost
(500 MW plant, medium S coal, 80% NO$_x$ removal)
Trend in SCR O&M Costs
(500 MW plant, medium S coal, 80% NO\textsubscript{x} removal)
Experience Curve for SCR Capital Cost

(500 MW coal plant, 80% NO\textsubscript{x} removal)

\[ y = 1.28x^{-0.18} \]

\[ R^2 = 0.75 \]

Cost reduction \( \sim 12\% \) per doubling
Experience Curve for SCR O&M Cost
(500 MW coal plant, 80% NO\textsubscript{x} removal, 65% CF)

\[ y = 1.87x^{-0.48} \]

\[ R^2 = 0.67 \]

- 1%  1  10  100  1000  10000

World fossil-fueled installed SCR capacity (GWe)

- 10  -9  -5  -3  -7

O&M cost (1997 constant Millions $/yr)

- 1.87x^{-0.48} \]

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Sources of SCR Cost Reduction

• Technological innovation
  ▪ Reduced catalyst installation cost
  ▪ Mechanized and automated catalyst manufacture
  ▪ Longer catalyst lives
    – Improved catalyst geometry and composition
    – Improved catalyst space velocity
    – Good \( \text{NH}_3/\text{NO}_x \) mixing and uniform distribution at the SCR reactor inlet
  ▪ New catalyst replacement strategies

• Increased manufacturing experience
• Competition among manufactures
• Lower catalyst prices
Key Findings & Conclusions (1)

- The cost of new generations of environmental technology has declined significantly with increased deployment and use worldwide.
- Environmental technology innovation has occurred in a global marketplace.
- The *stringency* of emission reduction requirements appears a major factor in *stimulating* and *directing* inventive activity in environmental technology.
- Learning by doing (operating experience at existing power plants) also led to significant declines in the operation and maintenance costs of environmental technologies.
Learning Rates for Energy Technologies

Source: McDonald and Schrattenholzer (2001), 42 technologies

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Results for CO$_2$ Capture Technology
Regeneration Heat Requirement for MEA-Based CO$_2$ Capture

![Graph showing the regeneration heat requirement for MEA-based CO$_2$ capture over a period from 1954 to 2002. The graph divides MEA concentrations into three categories: 5-12%, 12-20%, and 20-30%. The x-axis represents the year, and the y-axis represents the regeneration heat requirement in MBtu/tonne CO$_2$. The data points show a decreasing trend in heat requirement over time.]
Preliminary Capital Cost Estimates for Power Plant CO₂ Capture

(MEA-based system, 500 MW coal plant, 90% CO₂ removal, 2200 psia outlet)
Conclusions (2)

• Consideration of future cost reductions for carbon capture technologies can have a significant influence on the results of climate policy analyses.

• Future work will explore these effects in more detail, including the impact of alternative policy formulations on deployment of CO₂ capture and storage systems, and impacts on climate change mitigation costs.