Modeling the Diffusion of Carbon Capture and Storage

- Work in Progress -

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Agenda

1. Introduction
2. The Model
3. Experience Curves
4. Scenarios and Results
5. Conclusion
6. Literature
Introduction

- Coal will increase its share in energy supply (IEA 2007) due to the comparably large reserves and its even allocation around the globe
- So, technical solutions to transform coal fueled power plants into “low-carbon” plants are under development to mitigate its impact on climate
- CO$_2$ from large point sources, like fossil power plants, is captured, compressed, transported and stored (CCS) underground to isolate it from the atmosphere
- Those technologies cause significantly higher capital costs and lower efficiency. Thus, electricity producers miss economic incentives to apply the technology as long as carbon prices remain on a low level
- We therefore develop an economic, dynamic model to simulate the diffusion of CCS technology, while taking into account expected learning effects
The Model

• Diffusion of CCS is modeled in a perfect competition market, in which the producer chooses a welfare maximizing production portfolio of different generation technologies.

• Each technology is characterized by specific capital costs, efficiency, depreciation of capacity and CO$_2$ emission per MWh$_{el}$, which need to be covered by emission permits.

• Alternatively, producers can invest into CCS capacity. This leads to an emission reduction of 80% compared to the standard technology.

• Available technologies are: nuclear, coal, natural gas combined cycle, and coal CCS.

• The higher marginal generation costs of CCS electricity are assumed to decline over time through learning effects if the technology is applied.
Model Formulation

- Players face a linear inverse demand function of the form:

\[ P_t = \frac{a_t - D_t}{b_t} \]

\[ \sum_{g \tau \leq t} X_{g, \tau, t} = D_t = a_t - b_t P_t \]

\[ X_{g, \tau, t} = \text{Plants production of technology } g \text{ of age } \tau \text{ in } t \]

\[ fl_{g, \tau, t} \Delta t \text{CAP}_{g, \tau} + flex_{g, \tau, t} \Delta texcap_{g, \tau} \geq X_{g, \tau, t} \]

\[ fl_{g, \tau, t} = \text{age dependent fullload hours} \]

\[ CAP_{g, \tau} = \text{available capacity of technology } g \text{ of age } \tau \]

\[ flex_{g, \tau, t} \Delta texcap_{g, \tau} = \text{exogenous capacity} \]
Model Formulation

- Capacity depreciation modeled as decreasing availability of plants

\[
\begin{pmatrix}
0.95 & 0.91 & 0.86 & 0.81 & 0.75 & 0.69 & 0 & 0 \\
0.95 & 0.91 & 0.86 & 0.81 & 0.75 & 0.69 & 0 & 0 \\
0.95 & 0.91 & 0.86 & 0.81 & 0.75 & 0.69 & 0 & 0 \\
0.95 & 0.91 & 0.86 & 0.81 & 0.75 & 0.69 & 0 & 0
\end{pmatrix}
\]

\[f_{t,t}^{\text{fl}}\]

\[CAP_{g,(t+ilag_g)} = ICAP_{g,t}\]

\[ICAP_{g,t} = \text{investent into new capacity}\]

\[imax_g \geq ICAP_{g,t}\]

\[imax_g = \text{investment constraint}\]
Model Formulation

\[ E_{g,t} = \sum_{\tau, f(g, f) \in M} (1 - cpr_{g, \tau}) \cdot \theta_f \cdot \frac{X_{g, \tau, t}}{\eta_{g, \tau}} \]

\( E_{g,t} \) = Emissions of plant using technology \( g \)

\( cpr_{g,t} \) = Emission capture rate of technology \( g \)

\( \theta_f \) = carbon content of fuel \( f \)

\[ e_{\max_t} \geq \sum_{g} E_{g,t} \]

\( e_{\max_t} \) = exogenous emission restriction
Model Formulation

- We maximize sum of future discounted welfare with the discount factor $\beta$

Welfare is calculated as the integral under the demand curve less the production cost which consist of fuel and other variable cost as well as investment cost.

$$\max_{X_{g,\tau,t}, ICAP_{g,t}, CAP_{g,t}, E_{g,t}} \sum_t \beta^t \left\{ \int_0^{D_t(P_t)} P_t(D_t) dD_t - \sum_{(f,g) \in M, \tau \leq t} \left[ X_{g,\tau,t} \frac{p_f}{\eta_{g,\tau}} + c_g \right] - \sum_g PI_{g,t} * ICAP_{g,t} \right\}$$
Experience Curves

- A single factor learning curve captures the idea that technological performance improves when applied on large scale

\[ C_t = a \times CC_t^{-b} \]

\[ a = \frac{C_0}{CC_0^{-b}} \]

\[ b = \text{learning exponent} \]

- A study by Rubin et al (2006) indicates that the learning rate for CCS power plants capital costs could be expected around 10%
Modeling of Learning

\[ P_{I_{g,t}} = p_{i_{g,0}}^* \left( \frac{\text{cap}_{g,0}}{\text{cap}_{g,0} + \sum_{\tau < t} \text{ICAP}_{g,\tau}} \right)^{-\alpha_g} \]

\[ \alpha_{CCS} = 0.1 \]

\[ n_{g,t} = n_{g,0}^* \left( \frac{\text{gen}_{g,0}}{\text{gen}_{g,0} + \sum_{\tau < \tau, \tau < \tau} X_{g,\tau,\tau}} \right)^{-\gamma_g} \]

\[ \gamma_{CCS} = 0.015 \]
Scenario 3: Learning Effects Efficiency

Eta CCS

0.335 0.34 0.345 0.35 0.355 0.36 0.365 0.37

Cumulated Output [TWh]

Eta IGCC CCS
Learning Effects Capital Costs

CCS Coal

Cumulated Investment

€/kW

IGCC Coal
# Scenarios

<table>
<thead>
<tr>
<th>Scenario Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Case</strong></td>
</tr>
<tr>
<td>All market prices are held constant, no learning rates, all initial CO₂ emissions are covered by permits – allocation remains unchanged. Investment cap for the initially given technologies is adjusted according to the rate of capacity depreciation</td>
</tr>
<tr>
<td><strong>Scenario 1: Permit shortage</strong></td>
</tr>
<tr>
<td>Permit allocation is reduced by 2% each period to increase attractiveness of the low-carbon technology CCS.</td>
</tr>
<tr>
<td><strong>Scenario 2: Phase out of nuclear</strong></td>
</tr>
<tr>
<td>No investment into nuclear power plant capacity allowed</td>
</tr>
<tr>
<td><strong>Scenario 3: Learning effects</strong></td>
</tr>
<tr>
<td>Learning effects which lower capital costs and increase efficiency are implemented for both, renewables and CCS</td>
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</tbody>
</table>
Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Nuclear</th>
<th>NGCC</th>
<th>Lignite</th>
<th>Lignite CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time step</strong></td>
<td></td>
<td></td>
<td></td>
<td>2 years</td>
</tr>
<tr>
<td><strong>Full load hours</strong></td>
<td>[h/yr]</td>
<td>8000</td>
<td>5500</td>
<td>7500</td>
</tr>
<tr>
<td><strong>Fuel costs</strong></td>
<td>[€/MWh&lt;sub&gt;th&lt;/sub&gt;]</td>
<td>5</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>[%]</td>
<td>35</td>
<td>58</td>
<td>44</td>
</tr>
<tr>
<td><strong>Capital costs</strong></td>
<td>€/kW</td>
<td>2500</td>
<td>750</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td>[tCO&lt;sub&gt;2&lt;/sub&gt;/MWh&lt;sub&gt;el&lt;/sub&gt;]</td>
<td>0</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Life time</strong></td>
<td>Years</td>
<td>40</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>
Results Nuclear Electricity Production

Nuclear Energy Production

- Base Case
- Emi_res
- emis_res_learn

Time (MWh)

0 100 200 300 400 500 600 700 800 900

0 5 10 15 20 25 30
Results Coal Electricity Production

Coal Electricity Production

Time

MWh

Base Case
Emi_res
emi_res_learn
emi_res_nuc_phase-out
emi_res_nuc-phase-out_learn
Results Coal CCS Electricity Production

CCS-Coal Electricity Production

MWh

Time

emi_res_nuc-phase-out  emi_res_nuc-phase-out_learn

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Conclusion

• CCS shows lack of incentives for its application unless very stringent flanking polices (e.g. the phase out of nuclear energy production and a significant reduction in emission allowances) are implemented.

• The impact of learning effects is significant. The increase in efficiency by 34% to 37% for the CCS technology results in a higher investment into CCS.

• Consequently, market output in this scenario is higher compared to no learning which leads to higher rent for both, producers and consumers.

• Natural gas plays only a minor role in the CCS base-load scenarios

• Thus, public financed demonstration projects for expensive, emission reducing technologies are justified as long as they are flanked by stringent emission targets
Thank you for your Attention

Questions and Comments are welcome
References (Selected)


• NEUHOFF, Karsten (2008): Learning by Doing with Constrained Growth Rates and Application to Energy Technology Policy, University of Cambridge, EPRG Working Paper 0809


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• Rubin, E.S.;