Upstream v. Downstream CO₂ Trading in Electricity Markets: What is the Cheapest Way to Sustainability?

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EEM ‘10, Madrid, June 2010

Thanks to EPSRC FlexNet, US NSF, & CAISO for funding, and to Jim Bushnell (Iowa State U.), Frank Wolak (Stanford U.), Yihsu Chen (U. Calif.-Merced), & Andrew Liu (Purdue U.) for their collaboration

Outline

1. Who should be responsible for reducing carbon emissions?
   – Three proposals for carbon markets
   – Which is cheaper? Provides more incentive for conservation?
2. Method: Equilibrium models of electricity & carbon markets
3. Analytical results
4. Examples
   – Simple
   – Western US

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1. Who should be responsible for reducing CO$_2$?

Fuel extractors?
Oil producers/importers (US Waxman-Markey bill)

Power plants?
Power plants (EU Emissions Trading System)
US: Title IV SO$_2$; State greenhouse gas initiatives (RGGI)

Transmission grid/system operator?
In a single-buyer “POOLCO”-type power market

Retail suppliers/Load serving entities?
California, Western US “Load-Based” proposals
GEAC (Gillenwater & Breidenich 2009), CO$_2$RC (Michel & Nielson 2008)

Consumers?
 Tradable Quotas, Personal Carbon Allowances (Fleming, 1997)

Example: The California Debate

California AB32:
- CO$_2$ to be reduced to 1990 levels by 2020

Debate: “Point of Compliance” for CO$_2$
- i.e., Who’s responsible for “cap & trade”?
  - Power plants (sources)?
  - Load serving entities (LSEs) (for consumers)?
- Elsewhere, source-based dominates
  - Allocate allowances to power plants, & trade
    - Total emissions ≤ cap
- Load-based proposed for California
  - Mean emissions of LSE power purchases ≤ cap
    - Cheaper (Synapse Energy, 2007)?
    - Motivates more energy conservation (NRDC)?
  - Result in less CO$_2$ “leakage”??
- Concerns over effects on power trade motivated GEAC, CO$_2$RC
  - Generation Emission Attribute Certificates: Power plants sell power and emissions attributes separately to LSEs
  - CO$_2$Reduction Credits: LSEs pay power plants to reduce emissions
Source-Based Market Schematic

CO₂ Market

Emissions
Allowance Allocation
Emissions
Allowance Allocation

GenA

Power Sales

Consumers

Power Purchases

Power Sales

Power Purchases

GenB

Source-Based (Competitive) Market: Market Participants’ Optimization Problems

CO₂ Market:

\[ E_gA + E_{gB} \leq ALLOW_A + ALLOW_B + ALLOW_{Con} \]

(Price = \( p_{CO2} \))

GenA chooses \( g_A \geq 0 \):

\[
\max (p - C_A - p_{CO2}E_gA)g_A + p_{CO2}ALLOW_A
\]

= (Price – Fuel & Allowance Cost)*Sales + Allowance Value

Subject to: \( g_A \leq G_A \)

Generation \leq Capacity

\[ g_A = d_A \]

(Price = \( p_A \))

GenB chooses \( g_B \geq 0 \):

\[
\max (p - C_B - p_{CO2}E_{gB})g_B + p_{CO2}ALLOW_B
\]

s.t.: \( g_B \leq G_B \)

\[ g_B = d_B \]

(Price = \( p_B \))

Assume pure competition, no imports; What’s the equilibrium?

Consumers choose \( d_A, d_B \geq 0 \):

\[
\min p_Ad_A + p_Bd_B - p_{CO2}ALLOW_{Con}
\]

= Power Expenditures – Allowance Proceeds

s.t.: \( d_A + d_B \leq D \)
Source-Based Market Equilibrium Problem:
Find \( \{p_A, p_B, p_{CO2}; g_A, \mu_A; g_B, \mu_B; d_A, d_B, \lambda\} \) satisfying:

\[
0 \leq d_A \perp p_A - \lambda \leq 0 \\
0 \leq g_A \perp p_A - CA - p_{CO2}E_A - \mu_A \leq 0 \\
0 \leq \mu_A \perp g_A - GA \leq 0 \\

0 \leq d_B \perp p_B - \lambda \leq 0 \\
0 \leq g_B \perp p_B - CB - p_{CO2}E_B - \mu_B \leq 0 \\
0 \leq \mu_B \perp g_B - GB \leq 0 \\

d_A + d_B = D \quad (\lambda)
\]

10 Conditions, 10 Unknowns

Load-Based Market:
Market Participant Optimization Problems

**GenA chooses** \( g_A \geq 0 \):

\[
\text{MAX } (p_A - CA)g_A \\
\text{= (Price - Fuel Cost)*Sales} \\
s.t.: g_A \leq G_A
\]

**GenB chooses** \( g_B \geq 0 \):

\[
\text{MAX } (p_B - CB)g_B \\
s.t.: g_B \leq G_B
\]

Consumers choose \( d_A, d_B \geq 0 \):

\[
\text{MIN } p_A d_A + p_B d_B \\
s.t.: d_A + d_B = D \\
E_A d_A + E_B d_B \leq D \times E_{Rate_{\text{max}}} = E_{\text{max}} \quad (\text{dual } = p_{CO2})
\]

Emission weighted purchases \( \leq \) Limit

Derive equilibrium conditions:
10 Conditions, 10 Unknowns
Analytical Conclusions

Power prices:
- **Uniform in source-based system**: \( p_A = p_B \)
- **Differentiated in load-based system**
  - Higher for cleaner generation
  - \( p_i = p_0 - p_{CO2}^*E_i \)
    where \( p_0 \) = market price of zero-emissions power
- **Differentiation endangers efficiencies of PJM-like spot markets**
  - Single price markets chase clean power out to bilateral markets
  - Attract only dirty power, possibly a risk to reliability

All other variables identical:
- **Primal quantities (MWh, tons)**
- **Source-based** \( p_{CO2} \) = LSE’s shadow price of emissions

Proof:
- **Source based** \( \{p_0 - p_{CO2}^*E_i, p_{CO2}^*, g_A, \mu_A; g_B, \mu_B; d_A, d_B, \lambda\} \)
  satisfy equilibrium conditions of source-based (and vice versa)

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Analytical Conclusions

- “Load side carbon cap is likely to cost California consumers significantly less than supply side cap—Potentially billions of $/yr.”
  - By discriminating among suppliers and paying less for dirty power, LSEs can expropriate all profit increases due to emissions trading
  - Contrary to speculation, generator profits & net costs to consumers same
    … if allowances are auctioned to generators (\( \text{Allow}_A = \text{Allow}_B = 0 \)), and consumers get proceeds (\( \text{Allow}_\text{Con} = E_{\text{max}} \))
    … and if no damage to spot markets
- Two sources of emissions trading profits
  1. Emissions allowance rent = \( E_{\text{max}}^*P_{CO2} \)
  2. Rents to clean generation occur if regulation increases gross margin on sales:
    \[ (p - C_i - p_{CO2}E_i) > (p^{\text{NoReg}} - C_i) \]
    Load-based only transfers the first to consumers
Example: Source-Based (Competitive) Market:

All Allowances Auctioned, Proceeds to Consumers

**CO₂ Market:**

\[ 1 \times g_A + 0.5 \times g_B \leq 0.75 \text{ tons} \]

(Price = \( P_{CO₂} \) = $60/ton)

**Coal GenA:**

\[
\text{MAX} \ (p_A - $40/MWh - p_{CO₂} 1 t/MWh)g_A + p_{CO₂} * 0 \text{ tons} \\
= (\text{Price} - \text{Fuel & Allowance Cost}) \times \text{Sales} + \text{Allowance Value} \\
\text{s.t.: } g_A \leq +\infty \\
\text{Generation} \leq \text{Capacity}
\]

\[ g_A = d_A \] (Price = \( p_A \))

\[ = 0.5 \text{ MWh} \]

\[ = $40/MWh \]

**Gas GenB:**

\[
\text{MAX} \ (p_B - $70 - p_{CO₂} * 0.5)g_B + p_{CO₂} * 0 \text{ tons} \\
\text{s.t.: } g_B \leq +\infty
\]

\[ g_B = d_B \] (Price = \( p_B \))

\[ = 0.5 \text{ MWh} \]

\[ = $70/MWh \]

**Load-Based Market: Example**

**Consumers:**

\[
\text{MIN} \ p_A d_A + p_B d_B - P_{CO₂} * 0.75 \text{ tons} \\
= \text{Power Expenditures} - \text{Allowance Proceeds} \\
\text{s.t.: } d_A + d_B = 1 \text{ MWh} \\
\text{Emission weighted purchases} \leq \text{Limit}
\]

\[ = 100(0.5+0.5) - 60*0.75 = $55 \]

Dual = $100/MWh

**Coal GenA:**

\[
\text{MAX} \ (p_A - $40/MWh)g_A \\
= (\text{Price} - \text{Fuel Cost}) \times \text{Sales} \\
\text{s.t.: } g_A \leq +\infty
\]

\[ g_A = d_A \] (Price = \( p_A \))

\[ = 0.5 \text{ MWh} \]

\[ = $40/MWh \]

**Gas GenB:**

\[
\text{MAX} \ (p_B - 70)g_B \\
\text{s.t.: } g_B \leq +\infty
\]

\[ g_B = d_B \] (Price = \( p_B \))

\[ = 0.5 \text{ MWh} \]

\[ = $70/MWh \]

What is the equilibrium?

\[ = 40 \times 0.5 + 70 \times 0.5 = $55 \]

(Dual = $100/MWh)

\[ (\text{Dual} = p_{CO₂} = $60/MWh) \]

What’s the equilibrium?
Incentives for Energy Efficiency

• Does Load-Based Trading give greater incentives for conserving energy?
  – “Paint target on LSE’s back”

• Not in California
  – Utilities required to invest in energy efficiency if:
    \[ \text{Energy Efficiency Investment Cost} < \text{Avoided Cost of Energy} \times \text{Energy Savings} \]
  – In both load- and source-based systems, the “avoided cost of energy” (dual variable to the load constraint) is the same
    \[ = p_0 \text{ in the load-based case} = \$100/MWh} \]

• But if conservation also tightens LSE emissions constraint
  \[ E_A d_A + E_B d_B \leq D \times E_{Ratemax} \] then Load-Based weakens incentive
  – LSE saves $100/MWh in energy costs, but pays $60 more in CO2 control costs
    • Conservation saves just $40/MWh

Decoupling Proposal: CO2 Reduction Credits

• Concern with differentiating power by emissions
  – Harms spot-market type power market
  – CO2RCs and GEACs proposals to have consumers buy power & emissions separately

• CO2RCs: Plants sell 2 commodities to consumers:
  – Power is metered
  – CO2RCs are generated by power plants based on monitored emissions
    • Plant \( i \) generates \((K-E_i)g_i\)
    • \( K \) is a high “default” emissions rate
    • LSEs/consumers must buy \((K- E_{ratemax})D \) CO2RCs

• Variant: GEACs (sell MWh denominated GEACs, differentiated by emissions rate)
Generators Sell Power & CO₂RCs Separately

GenA chooses $g_A$, $CO₂RC_{s,A} \geq 0$:
\[
\text{MAX } (p_A - C_d)g_A + p_{CO₂RC}CO₂RC_{s,A}
\]
s.t.: $(K-E_r)g_A = CO₂RC_{s,A}$
CO₂RC Definition
\[
g_A < G_A
\]
\[
g_A = d_A \quad \text{(Price } p_A)
\]

GenB chooses $g_B$, $CO₂RC_{s,B} \geq 0$:
\[
\text{MAX } (p_B - C_d)g_B + p_{CO₂RC}CO₂RC_{s,B}
\]
s.t.: $(K-E_r)g_B = CO₂RC_{s,B}$
CO₂RC Definition
\[
g_B < G_B
\]
\[
g_B = d_B \quad \text{(Price } p_B)
\]

Consumers choose $CO₂RC_{buy}$, $d_A$, $d_B \geq 0$:
\[
\text{MIN } p_Ad_A + p_Bd_B + p_{CO₂RC}CO₂RC_{buy}
\]
s.t.: $d_A + d_B = D$
\[
CO₂RC_{buy} = (K-E_{ratemax})D
\]
Emission Reduction Credits = Reduction Target

Analytical Conclusions: CO₂RC

• CO₂RC is economically equivalent to source-based trading with the following (sometimes odd!) characteristics:

  – **Uniform power price for all producers:** $p_A = p_B$

  – **Producer output is subsidized:**
    • For each MWh generated, get $K$ free allowances
    • $K$ is a high “default” emission rate $> E_{ratemax}$
    • Decreases MC of power production, causing price of power to fall

  – **Too many allowances:** $\sum_i K g_i > \sum_i E_{ratemax} g_i = E_{ratemax}D$
    • $\therefore$ Consumers must pay generators for excess allowances, & “retire” them
    • Consumers pay generators $(K-E_{ratemax})p_{CO₂RC}D$

  – **Profits, Total consumer payments, amounts generated the same as original Source-Based**
    • Independent of default $K$
    • If zero price elasticity

• Basic source-based trading simpler – avoid LSE transaction costs
**CO₂RCs Example:**

\[ K = 1 \text{ ton/MWh} \ (> E_{\text{Ratemax}} = 0.75) \]

**Coal GenA:**

\[
\text{MAX } (p_A - 40)g_A + p_{\text{CO₂RC}}CO₂RC_{s,A} \]

s.t.: \( (1-1)g_A = CO₂RC_{s,A} \)

\( CO₂RC \) Definition

\( g_A < G_A \)

\( \text{Price } p_A = \$40/MWh \)

\( = 0.5 \text{ MWh} \)

\( = \$40/MWh \)

**Gas GenB:**

\[
\text{MAX } (p_B - 70)g_B + p_{\text{CO₂RC}}CO₂RC_{s,B} \]

s.t.: \( (1-0.5)g_B = CO₂RC_{s,B} \)

\( CO₂RC \) Definition

\( g_B < G_B \)

\( \text{Price } p_B = \$60/ton \)

\( = 0.25 \text{ tons} \)

\( = 0 + 0.25 \text{ tons} \)

\( = 0.25 \text{ tons} \)

\( = \$60/ton \)

**Consumers choose CO₂RC_{buy}, d_A, d_B \geq 0:**

\[
\text{MIN } p_Ad_A + p_Bd_B + p_{\text{CO₂RC}}CO₂RC_{buy} \]

s.t.: \( d_A + d_B = 1 \)

\( CO₂RC_{buy} = (1-0.75)1 \)

\( \text{Emission Reduction Credits > Reduction Target} \)

\[ \text{What is the equilibrium?} \]

\[ \text{Example: } K = 1 \text{ ton/MWh} \ (> E_{\text{Ratemax}} = 0.75) \]

\[ = 40*(0.5+0.5)+60*0.25 = \$55 \]

**Numerical Simulation with Power Imports**


- California imports 20% of power...and 50% of its power-based CO₂ emissions
- 3 California proposals (load, source, “first-seller”):
  - Do they lead to different emissions permits and whole electricity prices?
  - Do they yield different generator profits and consumer costs?
  - How do they compare in terms of contract-shuffling and CO₂ leakage?
- Method: Mixed complementarity model of equilibria in energy, transmission, emissions markets
Example: Network, Gen Mix and CO₂ Emissions

Zone A = Importer

Policy for Zone A: Target of 400 tons

Zone C (Exporter)

Results: Electricity Sales

- Net sales [MWh]
- Zonal sales [MWh]
- Electricity price [$/MWh]

No Cap

All Three Policies
Results: CO₂ Emissions

### Net CO₂ Flow

- **A:** 426 tons
- **B:** 30 tons
- **C:** 144 tons
- **A:** 422 tons
- **B:** 317 tons
- **C:** 278 tons

**Difference:**
- **A:** 83 tons
- **B:** 144 tons
- **C:** 175 tons

#### No-cap

<table>
<thead>
<tr>
<th>A: credited emissions</th>
<th>B: total emissions</th>
<th>C: total emissions</th>
</tr>
</thead>
<tbody>
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<td>A: 426 tons</td>
<td>B: 422 tons</td>
<td>C: 951 tons</td>
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#### All Three Policies

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**Results:**

All Three Policies results in higher CO₂ emissions compared to No-cap.

### CO₂ Leakage

**CO₂ leakage:** % of credited CO₂ reductions that are not real

\[
\% \text{leakage} = 100\% \left(1 - \frac{\Delta T}{\Delta A}\right)
\]

- **T₀:** total emissions | no cap
- **T₁:** total emissions | policy
- **A₀:** A’s “credited” emissions | no cap
- **A₁:** A’s “credited” emissions | policy

**Occurs because “contract shuffling” results in large apparent reductions in import-associated emissions that are not real**

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<tr>
<th>3 Approaches</th>
<th>%Leakage</th>
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<tbody>
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<td>85%</td>
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**Additional: University Logos**
Results: Contract-shuffling

Contrast shuffling: re-arrangement of electricity imports contracts results in apparent, but not real emissions reductions

\[
\Delta BC = 100\% (1 - \frac{\Delta BC}{\Delta I})
\]

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<td>%Shuffling</td>
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All emissions “reductions” associated with imports are imaginary

Conclusion: Comparison of Systems

- If economic rent of allowances is retained by consumers, three proposals are economically equivalent (nodal prices, consumer costs, social welfare, etc)
  - E.g., auction allowances in Source-based system, proceeds go to consumers
  - Load-based more complex, can endanger spot power markets
- All proposals subject to CO₂ leakage & contract shuffling
- US Federal Legislation needed!