Designing CO$_2$ Markets for the Power Sector:

Does It Matter

Who Must Comply and
Who Gets the Allowances?

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Background

Q1: Does It Matter Who Must Comply?
   – Load or Generators?

Q2. Does It Matter How Allowances Are Allocated?
    – Grandfathered or free to new investment?
Climate Warming Impacts: Example

- The famous spaghetti farmers of Switzerland & Italy no longer raise the crop.

- Speculation: Climate warming causing spread of the spaghetti weevil (*Marinarus meetbollus*).

For more information, see news.bbc.co.uk/onthisday/hidates/stories/april/1/newsid_2819000/2819261.stm

Source: BBC, April 1, 1957
Power: 60% of U.S. Energy CO$_2$

Figure 4. Electricity generation by fuel, 1980-2030 (billion kilowatthours)

History

Electricity demand

1980 2,094
2030 5,149

Projections

Coal

Nuclear
Natural gas
Renewables
Liquids

USDOE EIA, 2008 Annual Energy Outlook (draft)
How to Incent CO$_2$ Reductions?

1. **Command-and-Control, e.g.,**
   - Required fuels, equipment retrofits
   - Operating restrictions

2. **Individual facility caps**

3. **Emissions taxes**

4. **Cap & trade**
   - Overcompliers can sell excess permits to undercompliers
   - Permits allocated by auction or potlatch

5. **Consumer choice**

- Taxes, cap & trade create a “level playing field”
  -- Preferred from an efficiency point of view (NAS/NRC, 2004)

- C&T easy to impose on utilities
  --Taxes more appealing for other sectors
EU Emissions Trading System

- 27 Countries: Phase I: 2005-07; Phase II: 2007-2012
- Each allocates allowances ("National Allocation Plans")

![Graph showing bulk power prices +50%]

Source: J. Sijm, Netherlands Energy Research Centre, personal communication
State Programs in the U.S.

Goals:
- RGGI: -10% by 2019
- CA: 1990 levels by 2020

Design Issues:
- Who should be responsible for emissions?
- Who should be given the allowances? (“rent seeking”)
- Effectiveness (“leakage,” “contract shuffle”)
- Cost
Q1: Who should be responsible for CO₂ compliance?

- California AB32 Challenges:
  - Power only responsible for 20% of CO₂ there
  - Large amounts of imports

- Focus of policy debate: “Point of Compliance” for CO₂ allowance “cap and trade” system [http://docs.cpuc.ca.gov/efile/PD/78643.pdf]
  - Load serving entities (LSEs) or power plants (sources)?
  - Elsewhere, source-based dominates
    - Allocate allowances to power plants, and then trade
      - Total emissions can’t exceed cap
    - E.g., Title IV SO₂ program, RGGI
  - Load-based proposed for California
    - Mean emissions of LSE power purchases ≤ cap
    - Cheaper (Synapse Energy, 2007)?
    - Provide more motivation for energy efficiency (NRDC)?
Model Structure: “Complementarity Models”

Multifirm Market Models

- **In-State Generator:** Produce Power and Emissions
- **In-State Consumer:** Demand for Power (& Emissions)
- **Out-of-State Supplier:** Produce Power and Emissions
- **Out-of-State Consumer:** Demand for Power
- **Transmission System Operator**
- **Market Clearing Conditions for Power, Transmission Services, & Emissions**

Equilibrium calculation:
- Derive 1st order conditions for each market participant
- Add market clearing conditions
- Solve $n$ conditions for $n$ unknowns
Source-Based Market Schematic

CO₂ Market

Allowance Allocation

Emissions

Allowance Allocation

Emissions

GenA

GenB

Power Market

Power Sales

Consumers

Power Sales
Source-Based Market: Market Participant Optimization Problems

CO₂ Market:

\[ E_A g_A + E_B g_B \leq \text{ALLOW}_A + \text{ALLOW}_B \text{ (=} \text{CAP}) \]
(Price = \(p_{\text{CO}_2}\))

GenA chooses \(g_A \geq 0\):

\[
\text{MAX } (p_A - C_A - p_{\text{CO}_2} E_A)g_A + p_{\text{CO}_2}\text{ALLOW}_A
\]
subject to: \(g_A \leq \text{CAP}_A\)

GenB chooses \(g_B \geq 0\):

\[
\text{MAX } (p_B - C_B - p_{\text{CO}_2} E_B)g_B + p_{\text{CO}_2}\text{ALLOW}_B
\]
s.t.: \(g_B \leq \text{CAP}_B\)

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

\[
\text{MIN } p_A d_A + p_B d_B
\]
s.t.: \(d_A + d_B = L\)

Power Market

\[ g_A = d_A \text{ (Price = } p_A) \]
\[ g_B = d_B \text{ (Price = } p_B) \]
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:

\[
E_A g_A + E_B g_B \\
\leq ALLOW_A + ALLOW_B = CAP \\
(\text{price} = p_{CO2})
\]

\[
0 \leq g_A \perp p_A - C_A - p_{CO2}E_A + p_{CO2}\partial ALLOW_A/\partial g_A - \mu_A \leq 0 \\
0 \leq \mu_A \perp g_A - CAP_A \leq 0
\]

\[
0 \leq g_B \perp p_B - C_B - p_{CO2}E_B + p_{CO2}\partial ALLOW_B/\partial g_B - \mu_B \leq 0 \\
0 \leq \mu_B \perp g_B - CAP_B \leq 0
\]

\[
g_A = d_A \\
(\text{price} = p_A)
\]

\[
g_B = d_B \\
(\text{price} = p_B)
\]

\[
0 \leq d_A \perp p_A - \lambda \leq 0 \\
0 \leq d_B \perp p_B - \lambda \leq 0 \\
d_A + d_B = L - (\lambda)
\]
**Load-Based Market:**

**Market Participant Optimization Problems**

**GenA chooses** $g_A \geq 0$:  
\[
\text{MAX} \ (p_A - C_A)g_A \\
\text{subject to: } g_A \leq CAP_A
\]

**Consumers choose** $d_A, d_B > 0$:  
\[
\text{MIN} \ p_A d_A + p_B d_B \\
\text{s.t.: } d_A + d_B = L \\
E_A d_A + E_B d_B \leq L \times \text{Rate} = \text{CAP}
\]

**GenB chooses** $g_B \geq 0$:  
\[
\text{MAX} \ (p_B - C_B)g_B \\
\text{s.t.: } g_B \leq CAP_B
\]

**Power Market**

$g_A = d_A$  
(Price = $p_A$)

$g_B = d_B$  
(Price = $p_B$)
Analytical Conclusions

For single jurisdiction (no power imports), power prices:
- Same for all sources in source-based system
- Differentiated in load-based system
  - higher for cleaner generation
  - endangers efficiencies of PJM-like spot market

Allowance prices the same under load- and source-based

“Load side carbon cap is likely to cost California consumers significantly less than supply side cap—Potentially billions of $/yr.”

- Contrary to speculation, net costs to consumers same
- ... If allowances are auctioned to generators, and consumers get proceeds
  - ... if no damage to spot markets
Above conclusions also apply when CO₂-constrained states trade power with non-constrained states (under certain conditions)

- Load- and source-based equally prone to “leakage”/”contract shuffling”
- Assumes consistent treatment of imports to/exports from constrained state:
  - Imports’ “emissions” come under the constraint
  - Exported generation must obtain allowances
Simulation Questions

Three 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 CO$_2$ leakage?
Numeric Example: Network, Gen Mix and CO₂ Emissions

Policy for Zone A: Target of 400 tons
Results: Electricity Sales

- **net sales [MWh]**
- **zonal sales [MWh]**
- ( ) electricity price [$/MWh]

No Cap

All Three Policies
Results: CO$_2$ Emissions

- **net CO$_2$ flow [tons]**
- **zonal CO$_2$ from generation [tons]**

### No-cap
- From A to B: 422 tons
- From B to C: 144 tons
- From C to A: 30 tons
- Total emissions from generation: 951 tons

### All Three Policies
- From A to B: 317 tons
- From B to C: 278 tons
- From C to A: 83 tons
- Total emissions from generation: 951 tons
**Results: CO$_2$ Leakage**

**CO$_2$ leakage:** % of credited CO$_2$ reductions that are not real

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

\(\Delta T\): total emissions | *no cap*

\(\Delta A\): A’s credited emissions | *no cap*

\(\Delta T\): total emissions | *policy*

\(\Delta A\): A’s credited emissions | *policy*

<table>
<thead>
<tr>
<th>3 Approaches</th>
<th>%Leakage</th>
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<tbody>
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<td></td>
<td>85%</td>
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**Occurs because “contract shuffling” results in large apparent reductions in import-associated emissions that are not real**
Results: Contract-shuffling

Contract shuffling: re-arrangement of electricity imports contracts shrinks actual emissions reductions

$\Delta I$: emissions import to A | policy

$\Delta BC$: emissions of B & C | policy

All emissions “reductions” associated with imports are imaginary

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<tr>
<th>3 Approaches</th>
<th>%Shuffling</th>
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<td>100%</td>
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Q2. How Does Allowance Allocation Affect the Efficiency & Cost of CO$_2$ Trading?

- **Huge rents at stake**

- **Allocation methods:**
  1. Auction (proceeds to government or consumers)
  2. “Grandfather” (free to producers, based on past decisions)
  3. “Contingent Allocation”/“Updating”: Free allocation to producers based on either investments or sales

- **How might alternative allocation rules affect outcomes?**
  - Generation mix
  - Costs & welfare
  - Consumer expenditures
“However, if the expansion of the generation park (by incumbents or newcomers) is associated with a free allocation of emission allowances, then players will base their long-term investment decisions on the long-term marginal costs, including the costs of the CO$_2$ allowances, but by subtracting the subsidy that lowers the required mark-up for the fixed costs ... On balance, the power price will not be increased (ceteris paribus).”


Is this true in an industry with time varying demand, no storage, and a mix of technologies?

- Will the least-cost generation mix still result, and all the allowances rent returned to consumers?
Grandfathering / auctioning efficient (in closed economy)

Sales-based subsidizes consumption, raises costs (Fischer, 2001)
  – But may be 2\textsuperscript{nd} best if commodity traded with non-regulated countries (Demailly & Quiron, 2006)

No distortion from allocating to new investment (NL CPB, 2005)
  – New entry results in lower prices, transfer of rents back to consumers
  – If single technology, zero price elasticity (Zhang et al., 2007)

Allocation to new investment can distort mix of new generation, invert dispatch orders, inflate costs (Ibid.)
  – Generation may be built to get free allowances
  – Distortion can be greater for milder emissions reduction
  – Depends on how discriminate among generation types

But such allocation can correct capacity market failures (Smeers, 2007)
Multiarea Complications

- Regulated regions trade power with unregulated
  - Which allocation schemes 2\textsuperscript{nd} best?

- Separately regulated regions trade with each other
  - Distort siting/energy trade if different allocation rules?
  - Artificial differences in allowances prices?

- Multiple trading regions under single allowances cap, but with different allocation rules
  - Distort trade?
  - Raise compliance costs?
  - Which combinations of rules are least compatible?
Compare:
- Complete grandfathering (or auction)
- Mix of grandfathering & contingent allocation (sales, investment)
  - Various combinations of rules for different regions
  - Regions in same emissions trading system, or different ones

Assume:
- Free entry long run equilibrium
- No market power, continuous capacity investments, no outages
- Transmission limitation between systems
  - Transmission capacity rationed efficiently
Model Structure

Emissions Market A

Generator $A_1$

Generator $A_f$

Energy Market, Region A

Customers A

$P_A$

$D_A$

Emissions Market B

Generator $B_1$

Generator $B_f$

Energy Market, Region B

Customers B

$P_B$

$D_B$

Allowances Trade

Transmission, Arbitrage
Find \{prices, allocations, gen/sales, capacity, transmission\} solving:

**Profit Maximization**, Generator $f$ in region $n$:

Given \{prices, allocation rules\}:

\[ \text{MAX} \quad \text{Revenue} - \text{Costs of Capacity, Allowances, Fuel} \]

**Market clearing**, Market $n$:

- Energy Supply = Demand
- Emissions Supply = Demand
- Allowances Allocated = Allowances Available, subject to “ratio rules”
- Capacity Supply = Demand

**ISO**:

Given \{power $p$\}:

\[ \text{MAX} \quad \text{value of transmission services provided} \]
Long Run Equilibrium for Energy/Transmission/Capacity/Emissions

Find \{p_{nt}^*, p e_{n}^*, p c a p_{n}^*, \alpha_{nf}^*, \beta_{nf}^*, a_{nt}, s_{nft}, c a p_{nf}^*\} solving:

**Profit Maximization, Generator \(nf\):**

Given \{p_{nt}^*, p e_{n}^*, p c a p_{n}^*, \alpha_{nf}^*, \beta_{nf}^*\}:

\[
\text{MAX} \sum_t [p_{nt}^* - MC_{nf} - p e_{n}^* (E_{nf} - \beta_{f}^*)] s_{nft} + (p c a p_{n}^* + \alpha_{f}^* p e_{n}^* - F_{nf}) c a p_{nf}
\]

s.t.: \(0 \leq s_{nft} \leq c a p_{nf}, \forall t\)

**Market clearing, Market \(n\):**

Energy Market: \(\sum_f s_{nft} + a_{nt} = d_{nt}(p_{nt}^*), \forall t\)

Emissions Market: \(0 \geq \sum_{f,t} E_{nf} s_{nft} - \bar{E}_n \perp p e_{n}^* \geq 0\)

Contingent Allowances Allocation: Either:

\(\sum_f \alpha_{nf}^* c a p_{nf} + E_{GFn} = \bar{E}_n; \alpha_{nf}^*/\alpha_{n1}^* = R_{nf}, \forall f \neq 1\) (entry)

\(\sum_{f,t} \beta_{nf}^* s_{nft} + E_{GFn} = E_n; \beta_{nf}^*/\beta_{n1}^* = R_{nf}, \forall f \neq 1\) (sales)

Capacity Market: \(\text{CAP}_n \leq \sum_f c a p_{nf} \perp p c a p_{n}^* \geq 0\)

**ISO:**

Given \{p_{nt}^*\}:

\[
\text{MAX} \sum_{n,t} p_{nt}^* a_{nt}
\]

s.t.: \(\sum_n a_{nt} = 0\)

\(\sum_n P T D F_{nk} a_{nt} \leq T_k, \forall k,t\)
Model Properties and Solution

- **Under mild conditions, a solution exists**
  - for single region versions
  - multiple region versions in process

- **Computation**
  - Rearrange and linearize nonlinear complementarity problem to obtain (a provably feasible) linear problem
  - Iterate until convergence; converged solution solves the original problem
Example. 3 Gen Types, 2 Regions

- **Emissions limit**: 40 MT/yr in each
  - 94% of unconstrained emissions

- **Elastic demand**
  - Price intercept of €1000/MWh
    \[ \varepsilon = -0.11 \text{ @ } P = \€100/MWh \]

- **1 GW transmission limit**

- **Generator assumptions:**
  - Same in each region

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<thead>
<tr>
<th>Technology</th>
<th>Fixed Cost (€/kW)</th>
<th>MC (€/MWh)</th>
<th>CO₂ (Ton/MWh)</th>
<th>Allowances to Investment (relative) (1/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Turbine</td>
<td>50</td>
<td>80</td>
<td>0.6</td>
<td>0.6</td>
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<tr>
<td>Combined Cycle (Gas)</td>
<td>75</td>
<td>40</td>
<td>0.35</td>
<td>0.35</td>
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<tr>
<td>Pulverized Coal</td>
<td>120</td>
<td>20</td>
<td>1</td>
<td>1</td>
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</tbody>
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10 GW Load

Load Distribution

@ \( p = €0/MWh \)

(20 x 436 hr periods)
Results: Least Cost Emissions Reduction

6% CO$_2$ Reduction

$\Delta$Cost = 0.4 €/MWh (0.8%)

$pe = 11$ €/ton
Results: 6% Emission Reduction
Same Mix of Grandfathering & Free Allocation to New Investment in Both Regions
Results: 6% Emission Reduction
Same Mix of Grandfathering & Free Allocation to New Investment in Both Regions

-10% 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
% Relative to 100% Grandfather

% Allowances Grandfathered

Coal
Combined Cycle
CT
Peak MW

Generation Cost
Allowance Price

Consumer Payments (relative to least cost)

Results: 6% Emission Reduction
Same Mix of Grandfathering & Free Allocation to New Investment in Both Regions

8760 hrs

Social cost of CO₂ limit: -- 40 times as large at @0% GF
Effects of Giving Away Allowances to New Investment

- **Can affect allowance prices**
  - distorting dispatch order

- **Investment distortion**
  - For %GF < 50%: *major* (overinvest--generation built to get allowances)

- **Increases social cost of CO₂ control**
  - At least doubles (under %GF = 0)
  - Distortion worse at *smaller* levels of CO₂ reduction
  - Power prices may not change; instead most of cost is loss of government allowance rent
Different Allocation Rules in Different Regions

Region A: Contingent: 100% Allowances to investment

\[ pe = €26/t \]

Region B: 100% Auctioned

\[ pe = €18/t \]
Different Allocation Rules in Different Regions

Region A:
Contingent: 100% Allowances to investment
\[ pe = €26/t \]

Region B:
100% Auctioned
\[ pe = €18/t \]

Social cost of CO₂ limit:
-- 0.9% (0.4€/MWh) of no-limit cost if both regions grandfather
-- 10 times larger (4.2€/MWh) if Region A gives allowances to new investment

Why?
-- Wasted investment (4400 MW CT)
-- Distorted dispatch, trade

Other effect:
Exaggerated value of transmission, allowance arbitrage
Example of Distortion from Mixed Rules at A and B

-6% CO₂ case: congestion price @1000 MW limit
  60,833 €/MW/yr

However, welfare decreases if more transmission
If add 2300 MW …
…welfare decreases by 210 M €/yr or …
… -89,000 €/MW/yr

Compare “efficient” (all auction/grandfather) rule:
  No congestion
Conclusion

- Equilibrium models provide general insights on relationships of proposed policies
- Q1: Under some conditions, load-, source-, & “first-seller” based CO$_2$ trading are economically equivalent
  - In terms of consumer costs, generation, emissions, efficiency
  - All proposals are subject to contract shuffling and CO$_2$ leakage
  - Assumes: consumers own allowances; no undermining of ISO markets
- Q2: Allocating allowances to new investment can distort:
  - Dispatch
  - Investment in both generation & transmission