Carbon Revenue Redistribution Strategies In Deregulated Power Markets

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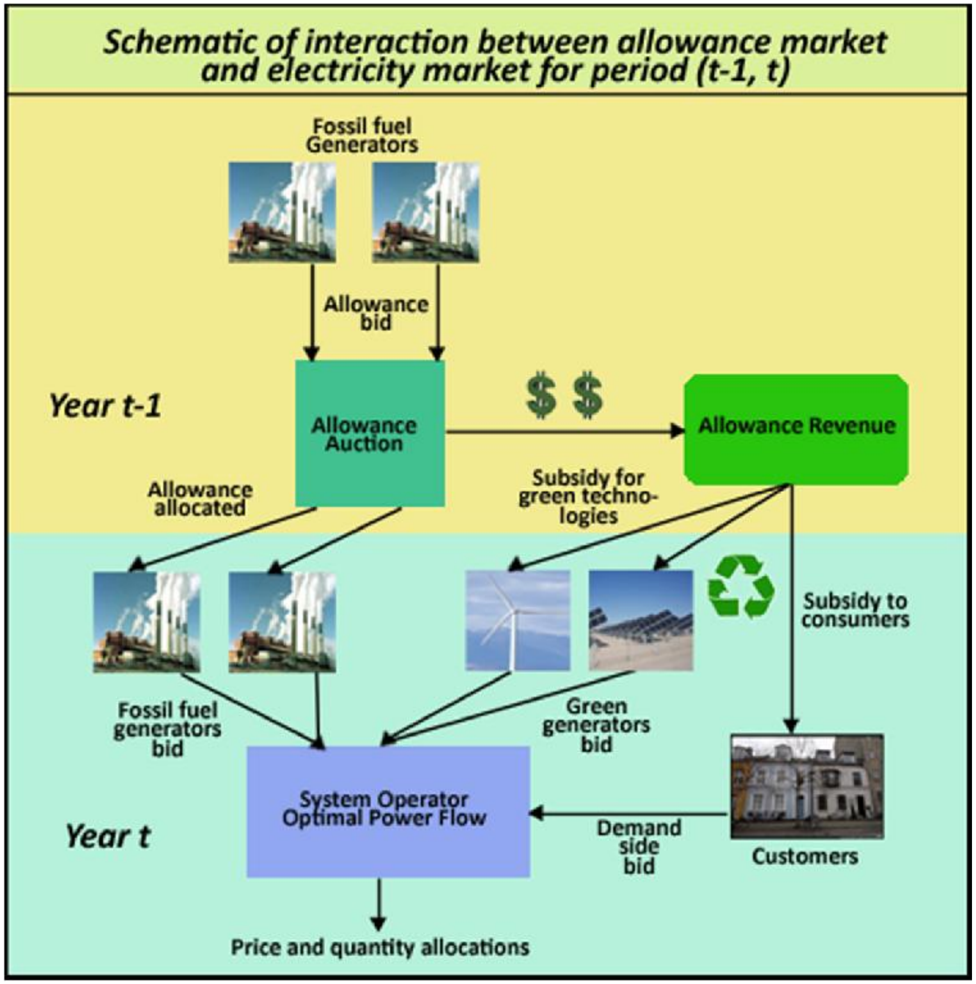
Motivation

- Carbon revenue redistribution is a feature common to cap-and-trade and carbon tax programs
- Amount of money collected would be significant (estimated $69 to $126 billion in first 5 years)
  - This is a new source of revenue
- Economists have argued in favor of redistributing the revenue to mitigate potential negative economic impact

Market Schematic



Potential Recipients

- Households (consumers)
  - Why? Electricity companies will pass on to the consumers the cost of allowances/carbon tax
  - $1,158 to $4,119 extra (in 1999 dollars) per household
- Low emission generators
  - Why? Need to increase market share of low-emission generators if emissions reductions are to be achieved
  - Targets for renewable based generation (EU 21%)

Literature (Households)

- Lump sum redistribution
  – Barnes and Breslow (2001)
- Reduction of distortionary taxes
  – Goulder (1995), Parry and Bento (2000)
- Lump sum redistribution more helpful for low-income families
  – Dinan and Rogers (2002)

Literature (low-emission gencos)

- Common in U.K., Denmark, Japan, Netherlands, among others
- Bills in the U.S. Congress have started considering these subsidies
  - Cantwell bill considers 25% or carbon revenue earmarked for clean energy investments
- Connecticut (RGGI Member) considers 23% of allowance auction revenue to support renewable energy programs

Our Model

- We consider:
  - Bid subsidies for low-emission generators
    - To lower consumer prices across the network
  - R & D subsidies for low-emission generators
    - To encourage sustained cost reduction for low-emission technologies (PV, wind, biomass, geothermal)

Our Model (continued)

Considers

- network constraints via Optimal Power Flow (OPF)
- multi-year horizon
- cap-and-trade (or carbon tax) implemented on a defined geographical region
- regional equity issues related to the "equal per capita redistribution rule"

Types of Subsidies

- Bid subsidies
  - Effect is realized during current year
- R & D subsidies
  - Effect is realized throughout the planning horizon
  - Knowledge stock is a function of cumulative stock (investment) Y of R & D

$$K(Y^t) = (\frac{Y^{t-1}}{Y^0})^\beta$$ (Fischer and Newell, 2008)

  - The impact of knowledge stock on production cost C is given by $K^{-1}C$

Types of Subsidies and OPF

- R & D subsidies
  - We define the reduction on production cost as:

$$R = C - K^{-1}C$$

  - Since the above expression is non-linear, we use a least squares approximation as

$$\hat{R} = \alpha K$$

where α is the regression coefficient

Mathematical Formulation

$$\max \sum \text{[Benefit to consumers]} - \sum_t \sum_h \sum_j \left(\text{[Cost to fossil-fuel generators]} \right. \quad (1)$$

Social Welfare Function

$$- \sum_t \sum_h \sum_k \left(\text{[Cost to green generators]} \right),$$

subject to:

$$Q_h^t - D_h^t - \sum_{l \in l(h)} (m_{hl}^t - m_{lh}^t) = 0 \quad \forall \ \text{node} \ \ h, t \quad (2)$$

$$\sum_{hl \in A(v)} R_{hl}^t (m_{hl}^t - m_{lh}^t) = 0 \quad \forall \ \text{voltage loop} \ \ v, t \quad (3)$$

Kirchhoff's laws Constraints (2)–(3)

$$Y_{k_h}^t - Y_{k_h}^{t-1} - y_{k_h}^t = 0 \quad \forall \ \ k, h, t \quad (4)$$

Cumulative R&D Constraints

$$Y_{k_h}^T \geq \beta_{k_h} \quad \forall \ \ k, h \quad (5)$$

Target R&D Constraints

$$\sum_h \sum_k q_{k_h}^t s_{k_h}^t + \sum_h \sum_k y_{k_h}^t \leq Z^t \quad \forall \ \ t \quad (6)$$

Yearly revenue Constraints

$$m_{hl}^t \leq M_{hl}^t \quad \forall \ \ \text{arc} \ \ hl, t \quad (7)$$

$$m_{hl}^t \geq 0 \quad \forall \ \ \text{arc} \ \ hl, t \quad (8)$$

Transmission Constraints (7)–(8)

$$q_{j_h}^t \leq \ Q_{j_h}^t \quad \forall \ \ j, h, \qquad q_{k_h}^t \leq \ Q_{k_h}^t \quad \forall \ \ k, h \quad (9)$$

$$q_{j_h}^t, q_{k_h}^t \geq 0 \quad \forall \ \ j, k, h \quad (10)$$

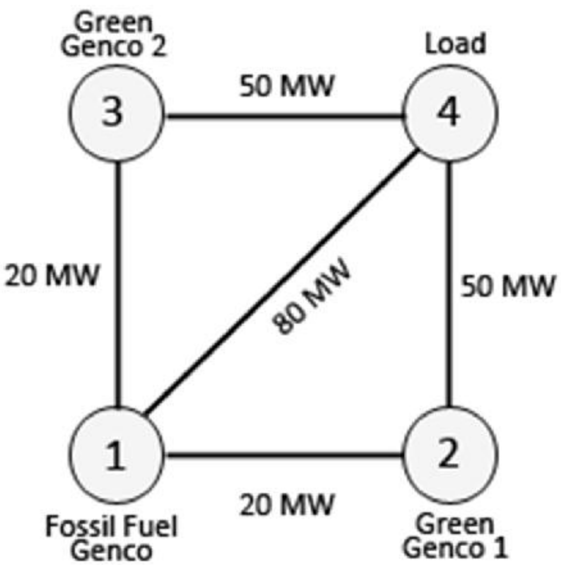
Generation Constraints (9)–(10)

Mathematical Formulation

- Objective function
  - Quadratic, non-convex
- Solved using
  - CONOPT3, MINOS, KNITRO

Model Application

- 4-node sample network
- Planning horizon: 5 years
- 2 low emission generators
- 1 fossil fuel generator
- 1 load



4-node sample network

Application

- 2 scenarios
  - discriminatory subsidies
  - non-discriminatory subsidies
- Allowance market scenario
  - perfectly competitive
  - allowances are sold at $3.38 in year 1
  - this price is increased 10% each year

Application

- Initial bidding parameters

Genco	e (\$/MWh)	f (\$/MWh^2)
Fossil Fuel	10.524	0.05
Green Genco 1	22	0.05
Green Genco 2	24	0.05
Load	**a**	**b**
Load 1	27	0.05

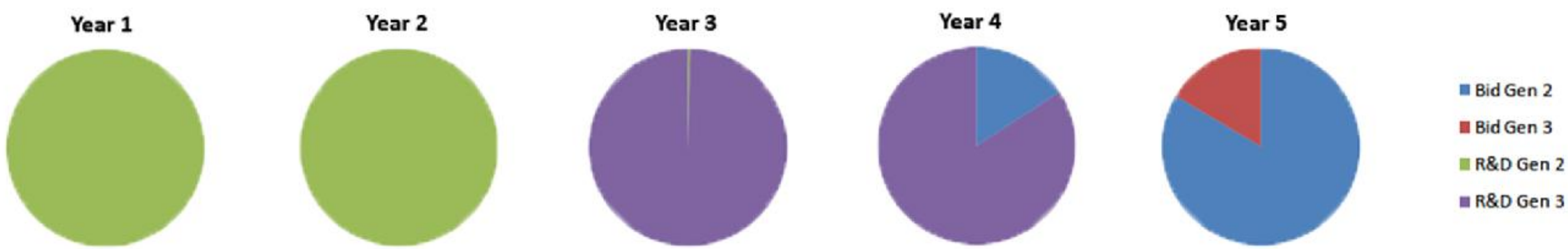
Initial bidding parameters

- R&D learning factors α_1=0.005176, α_2=0.006878

Recall that reduction in production cost (due to subsidies) is given by $\hat{R} = \alpha K$

Results

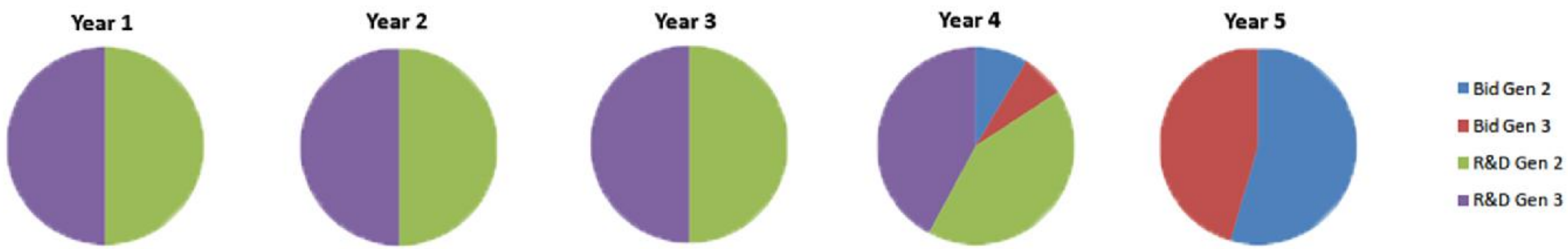
- Discriminatory subsidies Scenario



- R&D subsidies are allocated earlier, bid subsidies later, when fossil fuel bids are higher
- R&D subsidies for genco 2 are distributed earlier even though its α is lower

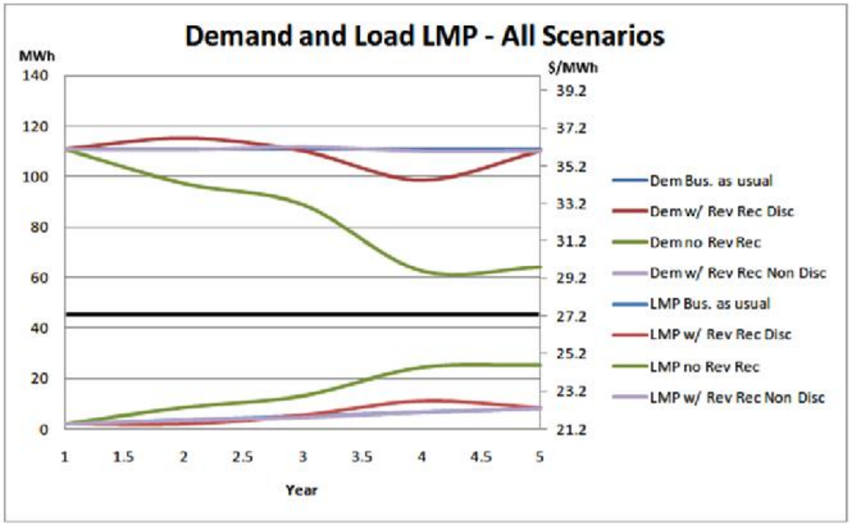
Results

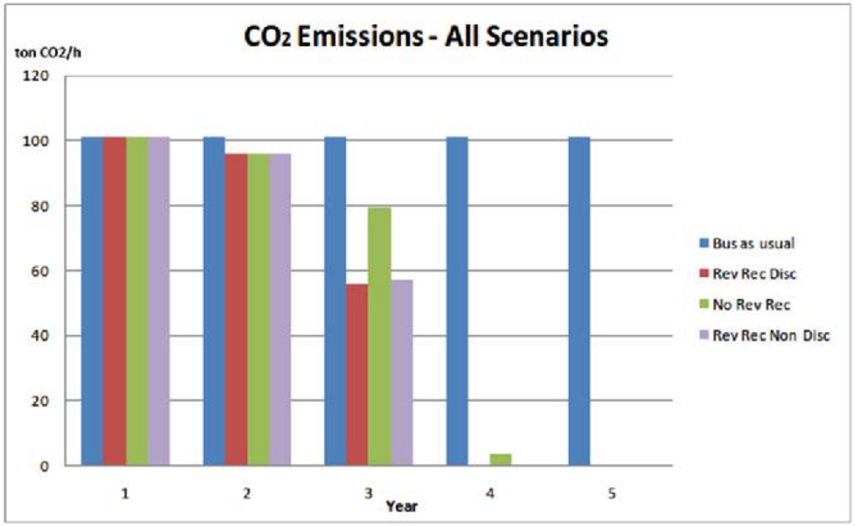
- Non-discriminatory subsidies Scenario



- R&D subsidies continue to be allocated earlier. Bid subsidies later
- Increased fairness in revenue redistribution at the expense of reduced total social welfare
- Since genco 2 produces more, total subsidies for genco 2 are higher

Results – All scenarios





Revenue recycling prevents demand from decreasing significantly without increasing carbon emissions and prices.

Summary

- We have developed a mathematical model for redistributing carbon revenue in a deregulated electricity market.
- In the example problem,
  - R&D subsidies are distributed earlier
  - location of generators in network plays a role in amount of subsidies allocated
  - revenue recycling strategy can be used to mitigate demand reduction without increasing emissions and prices

Thank you.

Questions?