Strategies for Redistribution of Revenue from CO_2 Emissions Control Schemes

Patricio Rocha, Felipe A. Feijoo, Tapas K. Das

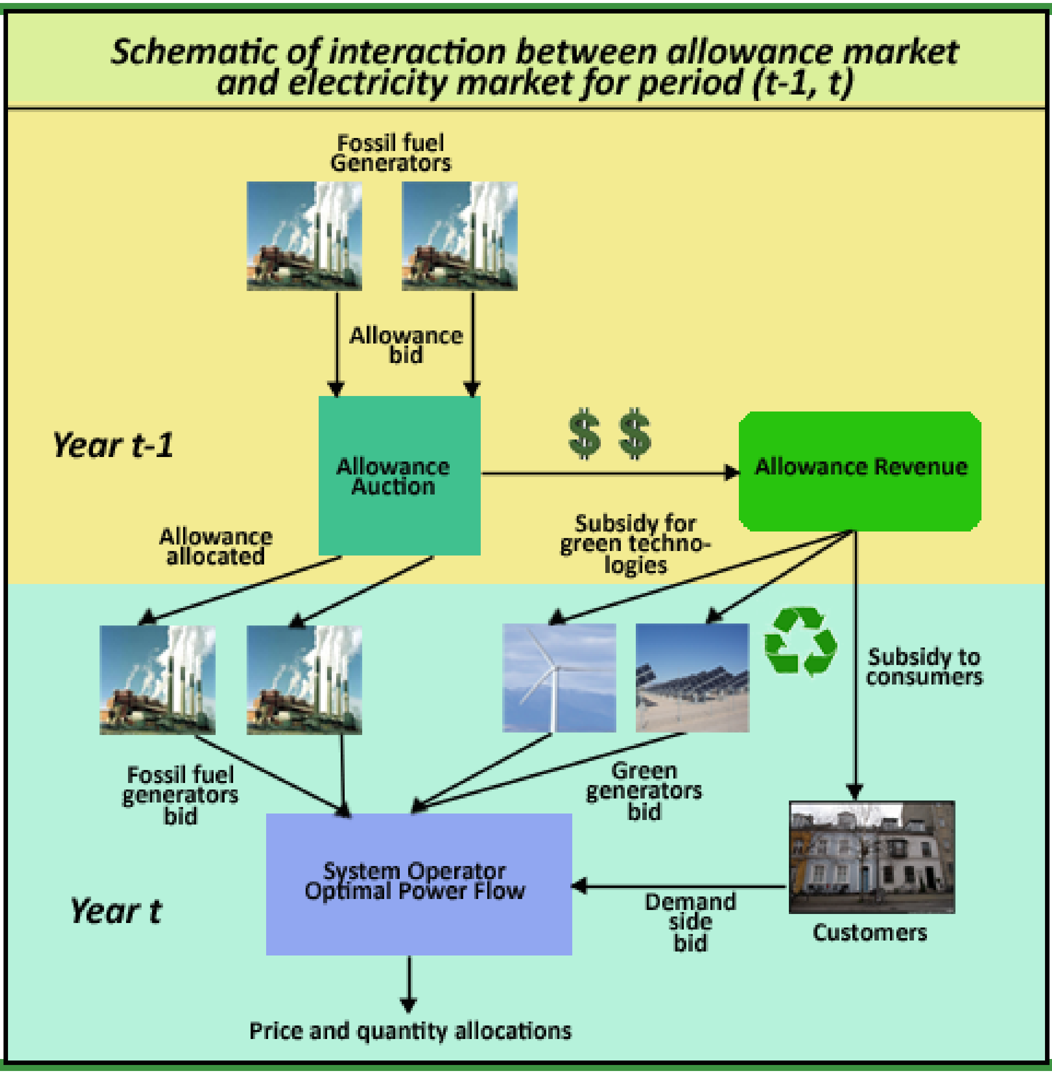
Industrial and Management Systems Engineering

University of South Florida

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)
- **What do we do with this new source of revenue?** *Economists have argued in favor of redistributing the revenue to mitigate electricity price increases and spur growth in low emission generation*

Market Schematic



Potential Revenue Recipients

- Households (consumers)
  - Why? Electricity companies will pass on to the consumers the cost of allowances/carbon tax
  - Estimated to be $1,158 to $4,119 extra (in 1999 dollars) per household
- Low emission generators
  - Why? Need to increase **zero-emission generation.**
  - Targets for renewable based generation (EU 21% by 2020)

Literature (revenue redistribution to households)

- There are two most discussed approaches:
  - *Lump sum redistribution* (Barnes and Breslow) (2001)
  - *Reduction of distortionary taxes* (Goulder (1995), Parry and Bento (2000))
- Lump sum redistribution would be more helpful for low-income families
  - Dinan and Rogers (2002)

Literature (revenue redistribution to 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% of carbon revenue earmarked for clean energy investments
- Connecticut (RGGI Member) considers 23% of allowance auction revenue to support renewable energy programs (Report: Investment of Proceeds from RGGI CO2 Allowances - 02/11)

Our Models

- Objectives
  - Growth of zero-emission generation
  - Reduction of prices for consumers
- We develop two models:
  1. To allocate bid subsidies for zero-emission generators via electricity auction
  2. To allocate R & D subsidies for zero-emission generators during electricity auctions within a planning horizon

Our Models (continued)

We consider

- Network constraints via DC Optimal Power Flow (DC-OPF)
- Demand side bidding
- Power network under a Cap-and-trade (or carbon tax) program

Types of Models

- Model 1: allocates bid subsidy
  - Effect is realized during current bidding period
  - Effect of the subsidy is prorated over the amount of power offered to the market by a low-emission generator. $(\alpha = \frac{1}{Q})$
- Model 2: allocates R & D subsidy
  - Effect is realized throughout the planning horizon
  - Effect is modeled using *knowledge stock* of a generator*:* a function of cumulative stock (investment) Y^t in R & D

$$K^t = (\frac{Y^{t-1}}{Y^0})^\beta$$

(Fischer and Newell, 2008)

with β the estimated learning elasticity

  - The impact of *knowledge stock* on production cost C at time *t* is given by

$$(K^t)^{-1} C$$

Types of Models (contd.)

- R & D subsidy
  - We define the reduction on production cost at time t as:

$$R^t = C - \left(\frac{Y^{t-1}}{Y^0}\right)^{-\beta} \; C$$

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

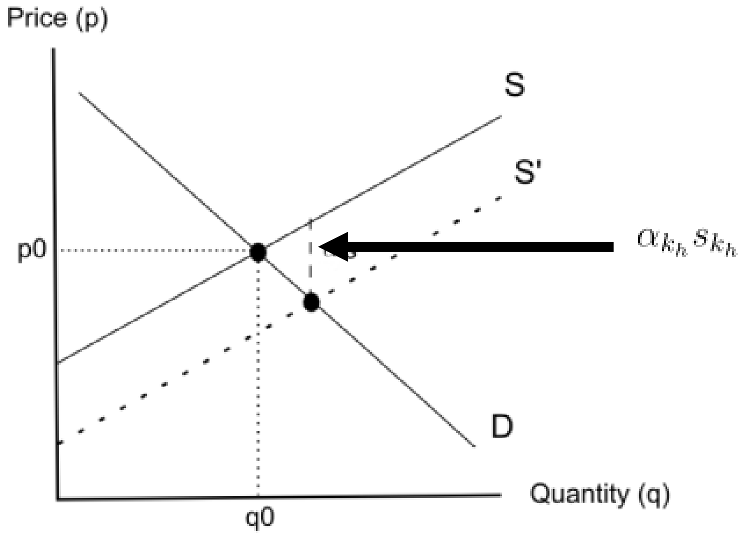
$$\hat{R}^t = \gamma\left(\frac{Y^{t-1}}{Y^0}\right)$$

where γ is the regression coefficient

Effect of subsidies

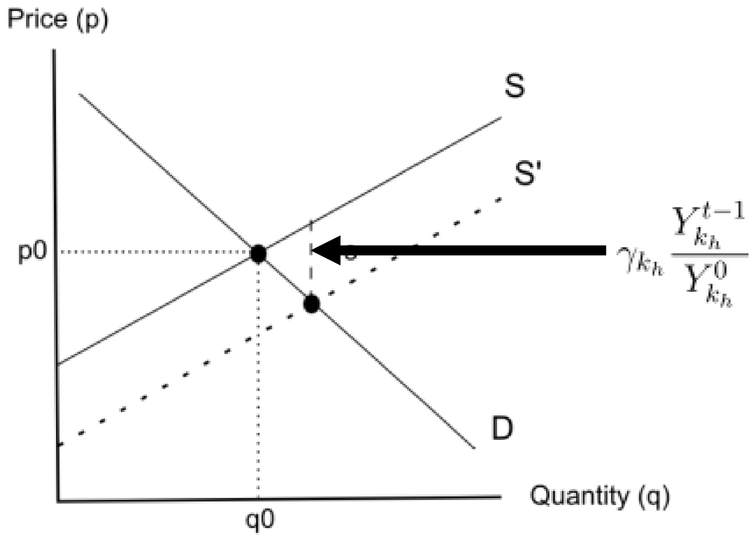
Model 1

- Bid subsidy for a single electricity auction



Model 2

- R & D subsidy for multiple electricity auctions within planning horizon



Model 1 - Formulation

$$\max \sum_h \sum_i \left(a_{i_h} - \frac{b_{i_h}}{2} d_{i_h}\right) d_{i_h} - \sum_h \sum_j \left(e_{j_h} + \frac{f_{j_h}}{2} q_{j_h}\right) q_{j_h}$$

$$- \sum_h \sum_k \left(e_{k_h} - \boxed{\alpha_{k_h} s_{k_h}} + \frac{f_{k_h}}{2} q_{k_h}\right) q_{k_h},$$

Social Welfare Function

subject to:

$$\sum_j q_{j_h} + \sum_k q_{k_h} - \sum_i d_{i_h} - \sum_{l \in l(h)} (m_{hl} - m_{lh}) = 0 \quad \forall \quad \text{node} \quad h$$

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

Kirchhoff's laws Constraints

$$\sum_h \sum_k s_{k_h} \leq Z$$

Revenue availability Constraint

$$m_{hl} \leq M_{hl} \quad \forall \quad \text{arc} \quad hl$$

$$m_{hl} \geq 0 \quad \forall \quad \text{arc} \quad hl$$

Transmission Constraints

$$q_{j_h} \leq \quad Q_{j_h} \quad \forall \quad j, h, \qquad q_{k_h} \leq \quad Q_{k_h} \quad \forall \quad k, h$$

$$q_{j_h}, q_{k_h} \geq 0 \quad \forall \quad j, k, h$$

Generation Constraints

Model 2 - Formulation

$$\max \sum_t \sum_h \sum_i \left(a^t_{i_h} - \frac{b^t_{i_h}}{2} d^t_{i_h}\right) d^t_{i_h} - \sum_t \sum_h \sum_j \left(e^t_{j_h} + \frac{f^t_{j_h}}{2} q^t_{j_h}\right) q^t_{j_h}$$

$$- \sum_t \sum_h \sum_k \left(e^t_{k_h} \boxed{- \gamma_{k_h} \frac{Y^{t-1}_{k_h}}{Y^0_{k_h}}} + \frac{f^t_{k_h}}{2} q^t_{k_h}\right) q^t_{k_h},$$

Social Welfare Function

$$\sum_j q^t_{j_h} + \sum_k q^t_{k_h} - \sum_i d^t_{i_h} - \sum_{l \in I(h)} (m^t_{hl} - m^t_{lh}) = 0 \quad \forall \ \text{node} \ \ h, t$$

$$\sum_{hl \in A(v)} R^t_{hl} (m^t_{hl} - m^t_{lh}) = 0 \quad \forall \ \text{voltage loop} \ \ v, t$$

Kirchhoff’s laws Constraints

$$Y^t_{k_h} - Y^{t-1}_{k_h} - y^t_{k_h} = 0 \quad \forall \ \ k, h, t$$

$$Y^T_{k_h} = \beta_{k_h} \quad \forall \ \ k, h$$

Target R&D Constraints

$$\sum_h \sum_k y^t_{k_h} \leq Z^t \quad \forall \ \ t$$

Revenue availability Constraints

$$m^t_{hl} \leq M^t_{hl} \quad \forall \ \ \text{arc} \ \ hl, t$$

$$m^t_{hl} \geq 0 \quad \forall \ \ \text{arc} \ \ hl, t$$

Transmission Constraints

$$q^t_{j_h} \leq \ Q^t_{j_h} \quad \forall \ \ j, h, \qquad q^t_{k_h} \leq \ Q^t_{k_h} \quad \forall \ \ k, h$$

$$q^t_{j_h}, q^t_{k_h} \geq 0 \quad \forall \ \ j, k, h$$

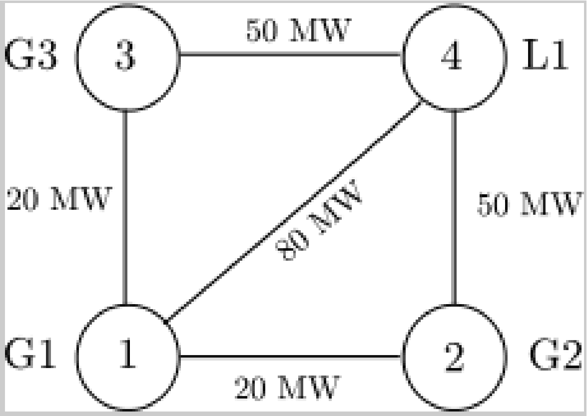
Generation Constraints

Formulations and Solution

- Objective function
  - Quadratic objective function, non-convex
- Solved using
  - Model 1
    - Piecewise linear approximations
    - CPLEX 12.1
  - Model 2
    - Backward induction (iterative procedure)
    - Piecewise linear approximations
    - CPLEX 12.1

Example Application

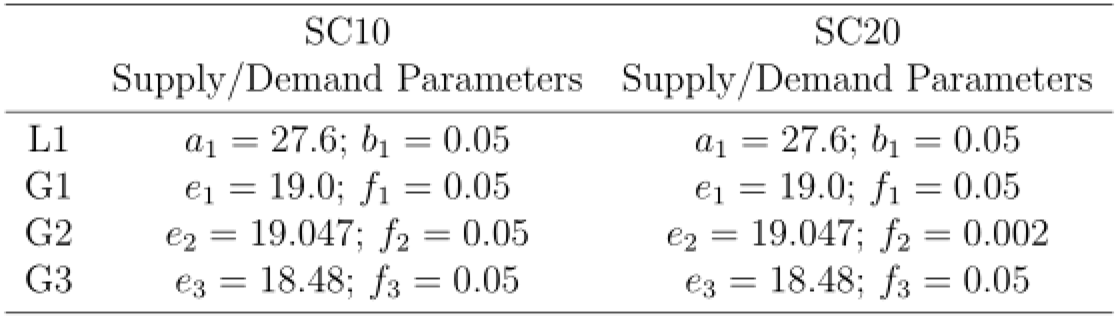
- 4-node sample network
- 2 zero-emission generators (G2 and G3)
- 1 fossil fuel generator (G1)
- 1 load (L1)



4-node sample network

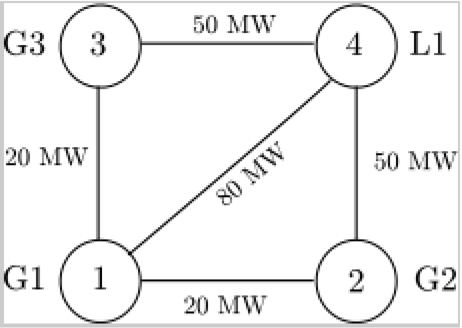
Application – Model 1

- Initial bidding parameters for two scenarios: SC10 (not congested) and SC20 (congested)

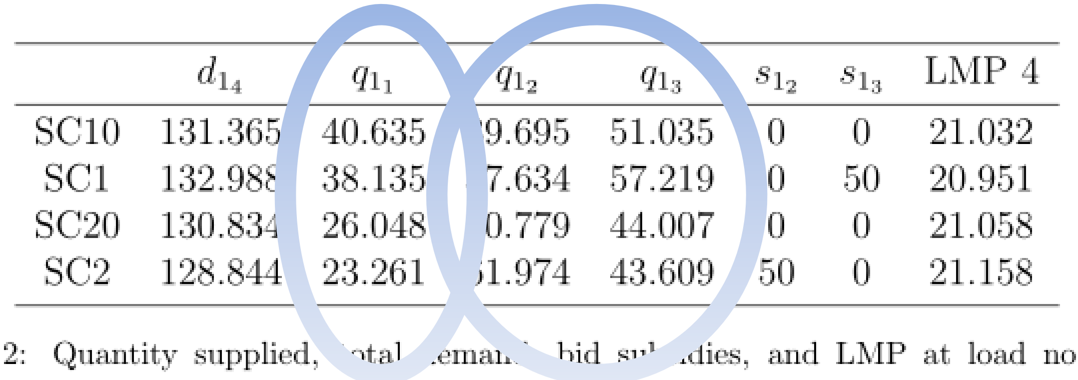


	SC10 Supply/Demand Parameters	SC20 Supply/Demand Parameters
L1	$a_1 = 27.6;\ b_1 = 0.05$	$a_1 = 27.6;\ b_1 = 0.05$
G1	$e_1 = 19.0;\ f_1 = 0.05$	$e_1 = 19.0;\ f_1 = 0.05$
G2	$e_2 = 19.047;\ f_2 = 0.05$	$e_2 = 19.047;\ f_2 = 0.002$
G3	$e_3 = 18.48;\ f_3 = 0.05$	$e_3 = 18.48;\ f_3 = 0.05$

Table 1: Supply/Demand curve parameters for generators and load in SC1 and SC2



Model 1 - Results



	d_{1_4}	q_{1_1}	q_{1_2}	q_{1_3}	s_{1_2}	s_{1_3}	LMP 4
SC10	131.365	40.635	9.695	51.035	0	0	21.032
SC1	132.988	38.135	7.634	57.219	0	50	20.951
SC20	130.834	26.048	0.779	44.007	0	0	21.058
SC2	128.844	23.261	1.974	43.609	50	0	21.158

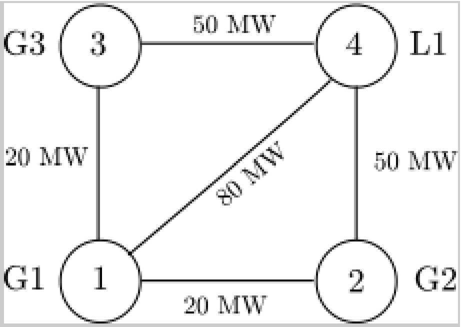
Table 2: Quantity supplied, total demand, bid subsidies, and LMP at load node for scenarios SC10, SC1, SC20, and SC2

- Total **low-emission generation is increased** and **emissions reduced**.
  - A $0.7/MWh subsidy results in a 4.5% (0.7%) increase in low emission generation in non-congested (congested) network.
  - A $0.7/MWh subsidy results in a 6.1% (10.6%) decrease in emission in non-congested (congested) network.
- Benefits of subsidies could differ significantly in congested vs non congested networks.

Application – Model 2

	Supply/Demand parameters
L1	$a_1^1 = 27.0;\ b_1^1 = 0.05$
G1	$e_1^1 = 10.524;\ f_1^1 = 0.05$
G2	$e_2^1 = 22.0;\ f_2^1 = 0.05$
G3	$e_3^1 = 24.0;\ f_3^1 = 0.05$

Table 3: Supply/Demand curve parameters for generators and load at $t = 1$

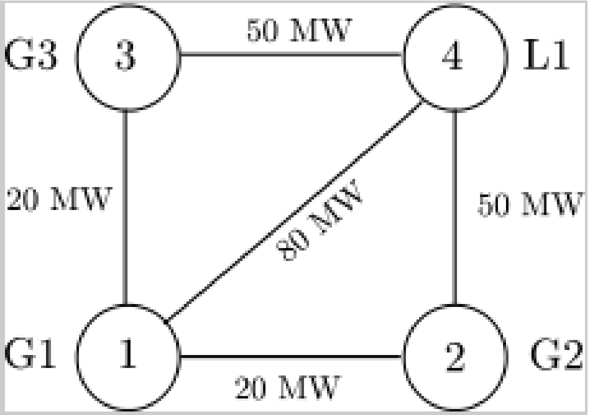


- R&D learning factors γ_2=0.005176, γ_3=0.006878

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

Application – Model 2 (ctnd.)

- Allowance market scenario
  - allowances are sold at $3.38 in period 1
  - this price is increased 10% each period
  - the cap (number of allowances) reduced 5% each period
  - planning horizon: 5 periods



Model 2 - Results

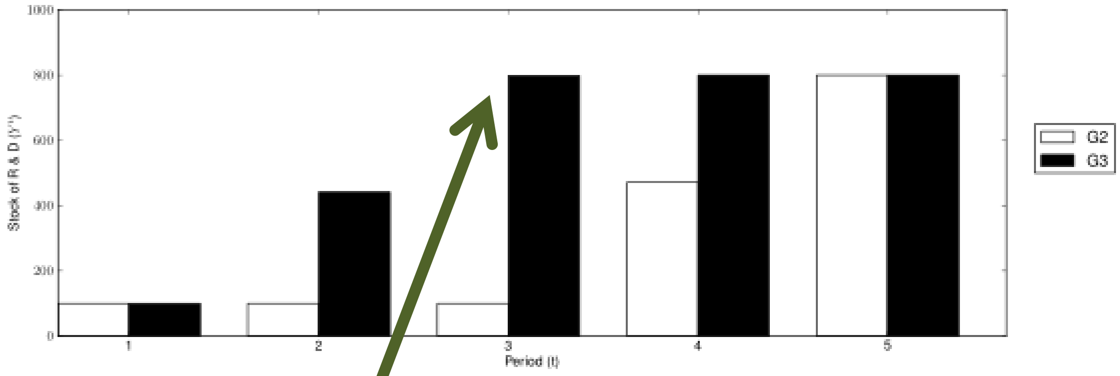
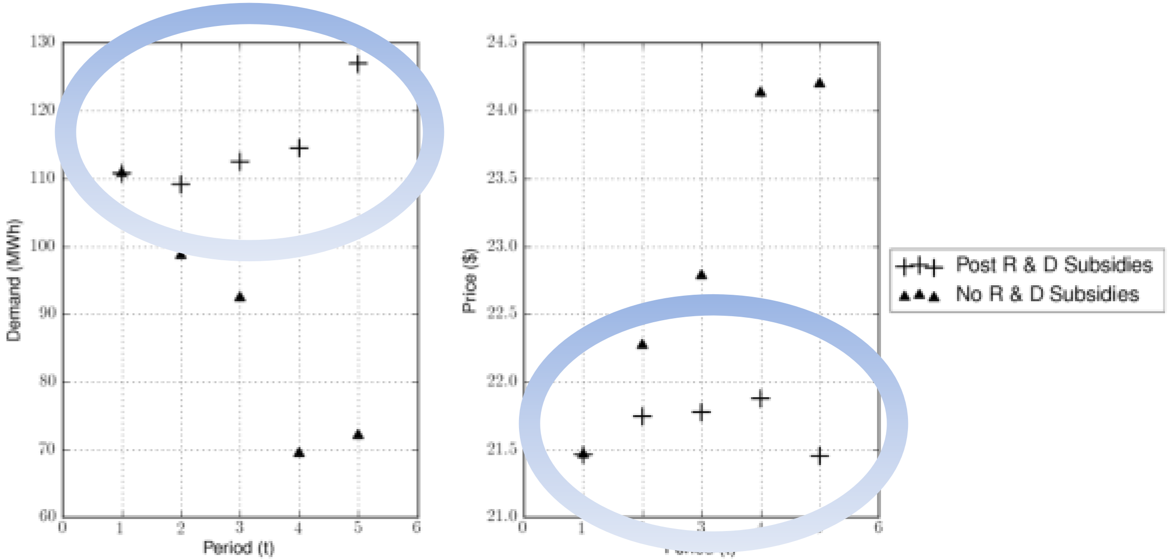


Figure 4: Stock of R & D throughout the planning horizon for each low-emission generator

- G3 reaches the R & D target earlier than G2,
- This is partly due to G3 translating R & D stock into production cost reductions at a higher rate $(\gamma_3 > \gamma_2)$

Model 2 - Results



- Consumers at the load node greatly benefit when R & D subsidies are allocated via higher demand (left) and lower prices (right).

Model 2 - Results

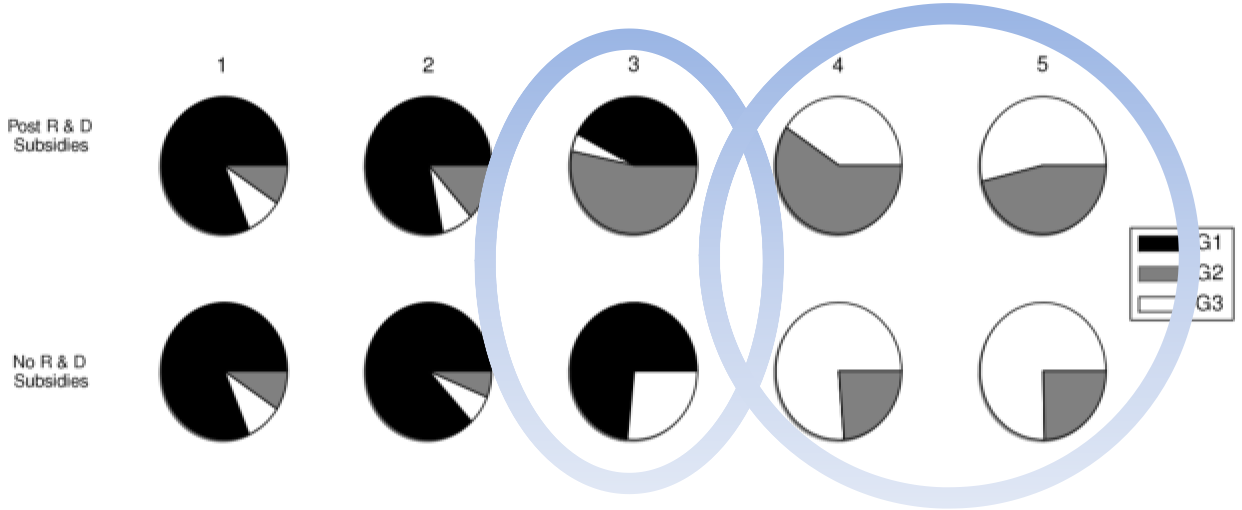


Figure 6: Market share of the generators in the scenario post R & D subsidies implementation and the scenario with no R & D subsidies

- Most clear effect of the R & D subsidy is observed at t = 3 (G1 loses a large share of the market)
- At t=4 and t=5, the R & D subsidies’ effect on market share is leveling the playing field between the two low-emission generators

Summary

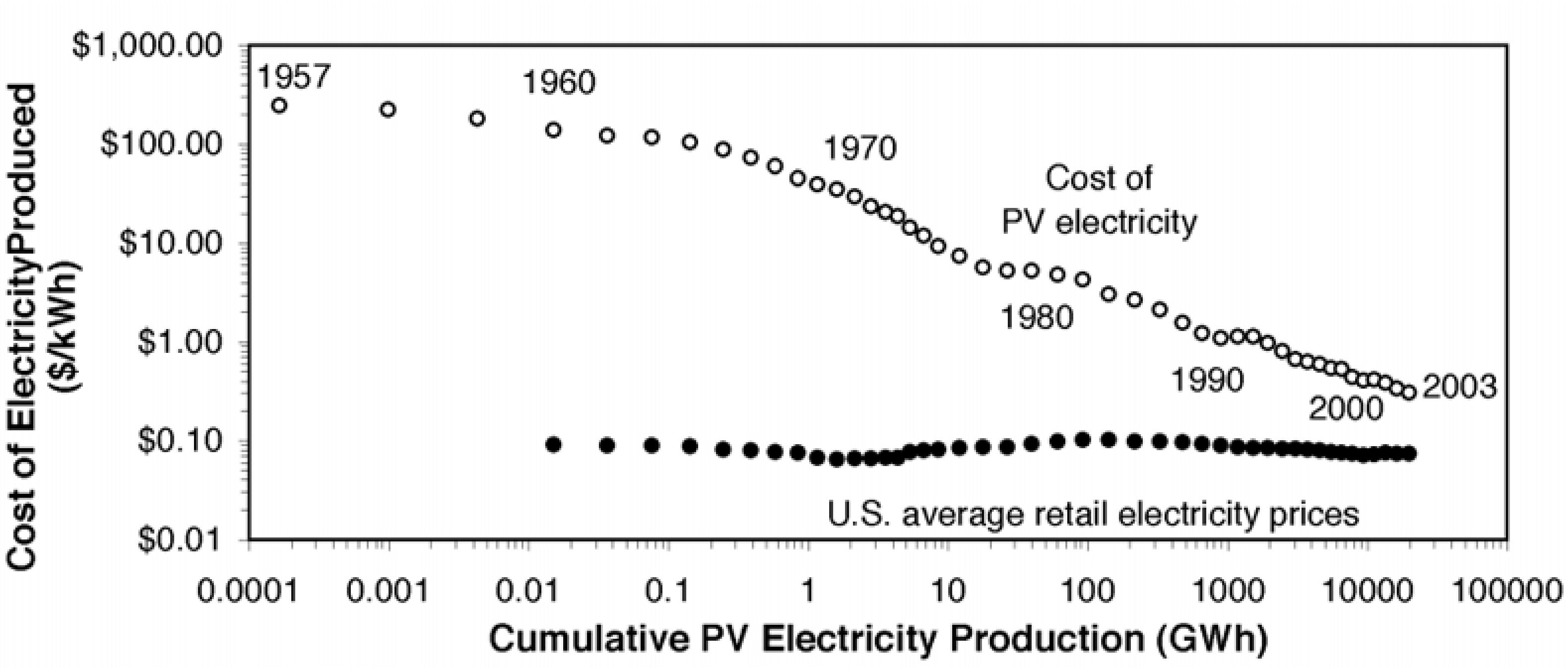
- We have developed a mathematical model for redistributing carbon revenue in electricity markets.
- From the example problem,
  - An average increase in load electricity price of 7% can be reduced to 1% by redistributing the carbon revenue to low-emission generators.
  - Total low-emission generation is increased 50% by allocating R & D subsidies to low-emission generators.
  - An equitable redistribution of the revenue is not the optimal way of carrying out the redistribution when social welfare is maximized.

Thank you.
Questions?

Learning Curves

- Describe how total costs decrease with cumulative production
- Progress ratio: rate at which costs are decreased for each doubling of cumulative production
- For instance, for PV modules the literature suggests historical progress ratios of 0.77-0.82 (Sandén , 2005)

Learning Curves



Nemet, International Energy Agency, 2007