PennState
College of Earth
and Mineral Sciences

John and Willie Leone Family
Department of Energy and
Mineral Engineering

Impact of Carbon Taxes on Strategic Investments in Imperfectly Competitive Electricity Markets

Brayam Valqui (bdv3@psu.edu), Chiara Lo Prete, and Mort Webster, The Pennsylvania State University

INTRODUCTION

A carbon tax policy is a market-based instrument that puts a price on carbon emissions, forcing emitters to recognize the social damages from production along with their private costs.

The impact of carbon taxes on the power sector has been widely analyzed assuming perfect competition. Thus, a Cost Minimization approach has been traditionally used to assess the impact of a carbon tax in the power sector. Yet, this approach does not hold in electricity markets (Figure 1), where the system operator does not have any control over the firms' investment decisions.

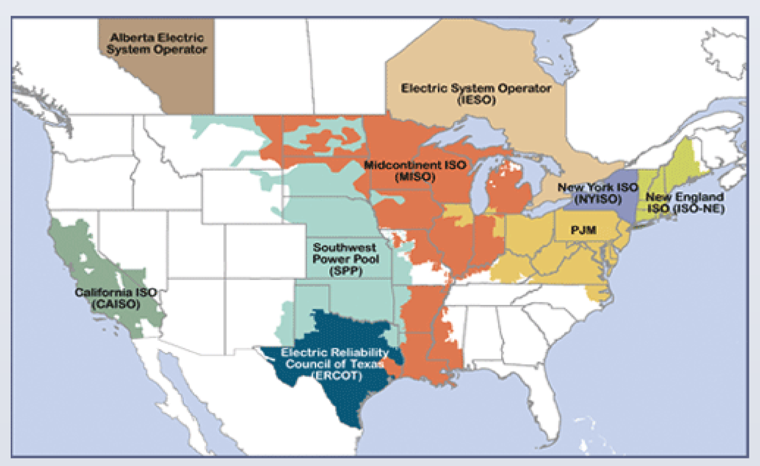

Figure 1: Electric Power Markets in the U.S. [1]

PROBLEM STATEMENT

There is imperfect competition in wholesale electricity markets. Since their introduction in the U.S. more than two decades ago, studies have shown that some firms can engage in strategic bidding to affect prices and increase their profits [2], [3].

However, a firm can also affect electricity prices and increase its profit through its investments. Strategic investment decisions refer to the optimal investment decisions derived by a firm such that these are the most beneficial and maximize the firm's profit [4].

Since a firm will have an incentive to invest in a portfolio of technologies such as it increases electricity prices and its profit, strategic investment behavior can change the portfolio of technologies in the system.

If there is a carbon tax in a competitive electricity market …

⇒Does strategic investment behavior change the long-term portfolio of technologies with respect to the cost-minimization approach? If so,

⇒Do these strategic investments impact the emissions reductions of the carbon tax policy?

- Bilevel model.
  - Upper Level: Firm i solves for its optimal investment decision.
  - Lower Level: ISO solves the market clearing problem.
- Bilevel model formulated as a Mathematical Program with Equilibrium Constraints (MPEC).
- Solve the set of interrelated MPECs, one for each firm, and find the Nash Equilibrium (Game Theoretic approach).

Figure 2: Cost Minimization approach used in Generation Expansion Planning

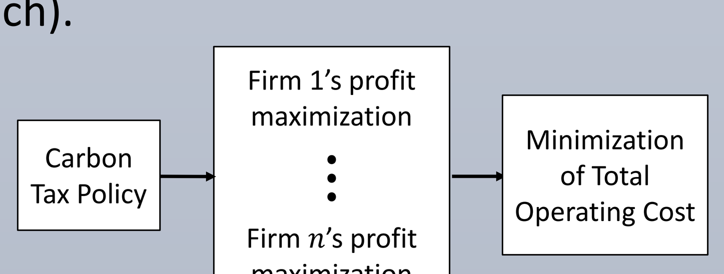

Figure 3: Proposed Game Theoretic approach

METHODOLOGY

The generation investment problem faced by each strategic firm is formulated as a bilevel model, whose upper-level problem represents the firm's investment decisions seeking to maximize its profit affected by a carbon tax, and whose lower-level problem represents the market clearing conditions under the presence of the same carbon tax.

Our bilevel model is a large-scale complementarity problem that is solved as a mixed-integer linear programming problem using a commercial solver (CPLEX).

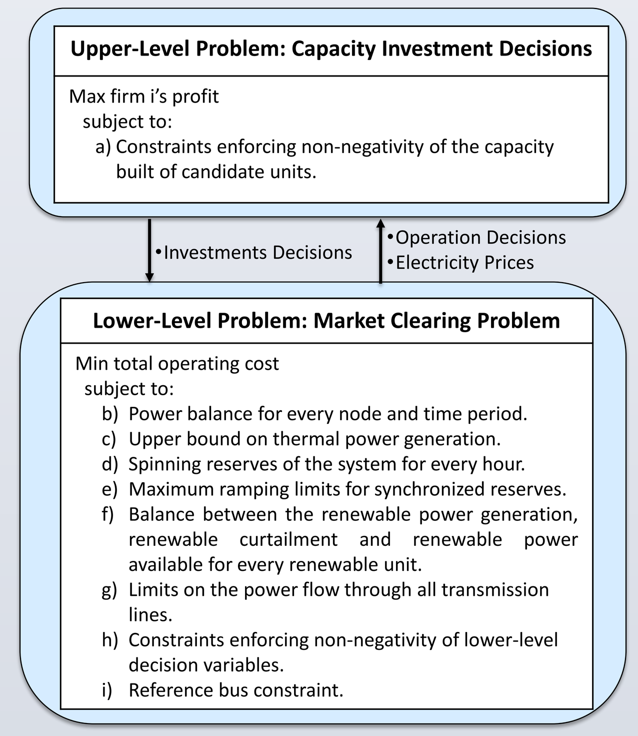

Figure 4: Bilevel model to solve for the optimal investment decisions of an strategic investor

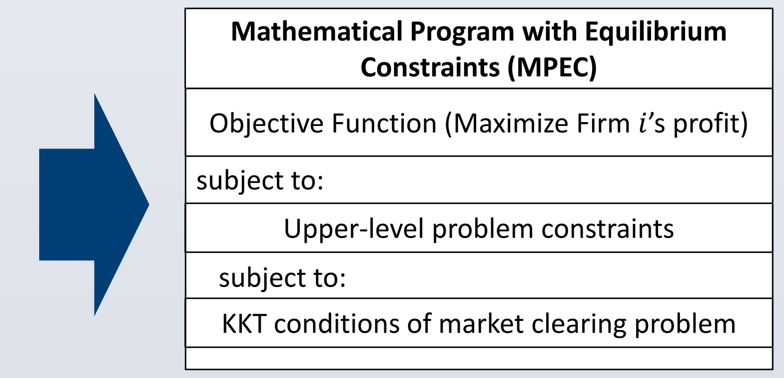

Figure 5: Bilevel model formulated as an MPEC

Why a Game Theoretic approach?

⇒Competition in the Electricity Market

- Several firms compete to produce electricity under imperfect competition.
- Firm i invests in new generation capacity.
  - ➢ It changes the system operator's decisions and electricity prices.
  - ➢ It affects other firms' decisions.
- Firms' problems (MPECs) are interrelated.
- Game Theoretic Approach allows to find the market equilibria.

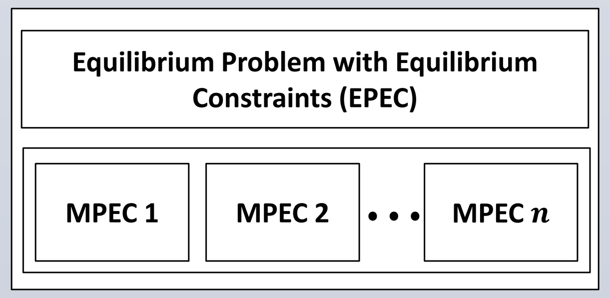

Figure 6: Conceptual formulation of an EPEC

Game Theoretic Approach

- Players: **Strategic investors in electricity markets.**
- Strategies: **Investment decisions in new generation capacity for each candidate technology.**
- Payoffs: **Profits.**

Find a strategy profile ($s^*_1, s^*_2, \ldots, s^*_n$) such that, for each player $i = 1,2,\ldots,n$, s^*_i is a best response to the other player's equilibrium strategies s^*_{-i}.

Solution algorithm: diagonalization (keep going until no change!)

Nash Equilibrium

An EPEC can have multiple equilibrium solutions. We used the following approach to select a representative Nash Equilibrium.

Step 1: Randomly select several starting points to initialize the diagonalization algorithm.

Step 2: Run the diagonalization algorithm several times considering the starting points in Step 1. Compute the sum of profits for each Nash Equilibrium solution.

Step 3: Pick the equilibrium solution that leads to the highest sum of profits.

RESULTS

Several carbon tax scenarios were considered. We solved for the optimal investment decisions under the Cost Minimization approach (Figure 7) and the Game Theoretic approach (Figure 8). Both figures show the total investment decisions under each scenario, which are different for both approaches. The results in Figure 8 represent the investments under the Nash Equilibrium.

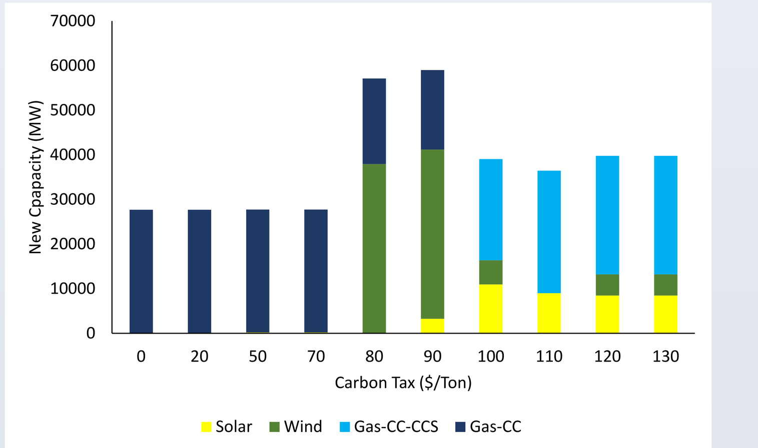

Figure 7: Investment decisions under the Cost Minimization approach

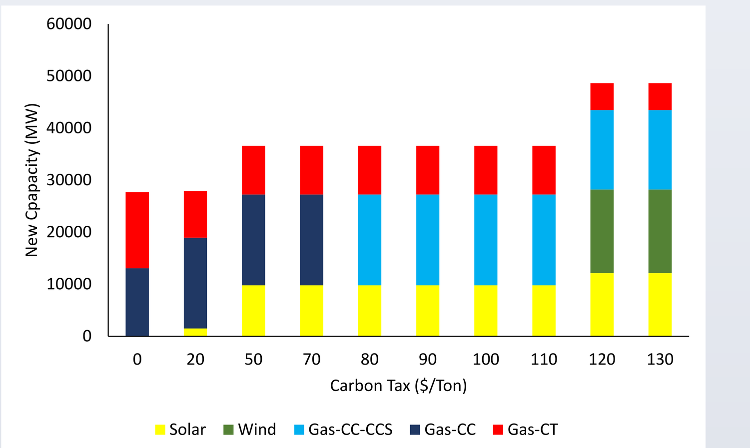

Figure 8: Investment decisions under the Game Theoretic approach

Under the Game Theoretic approach, firms realize that by investing more in a high-cost technology (Gas-CT), they can increase prices and obtain higher profits. The consequence of that is higher emissions under low carbon taxes and high carbon taxes, but similar emissions levels under taxes within the range from 50 to 90 $/Ton (Figure 9). On the other, as expected, the total system cost is lower under the Cost Minimization approach (Figure 10).

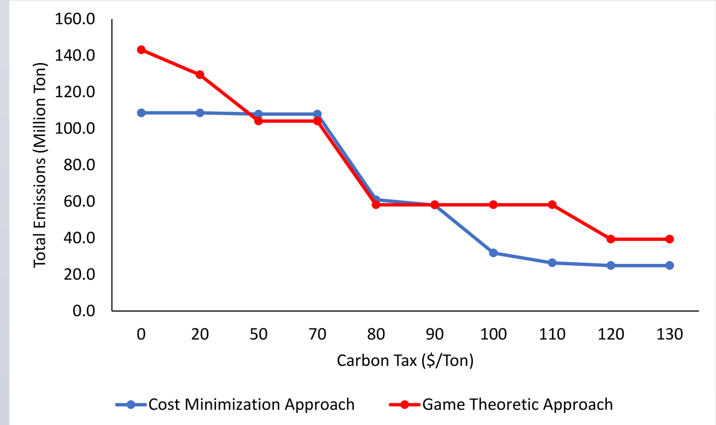

Figure 9: Total CO_2 emissions: Cost Minimization approach vs. Game Theoretic approach

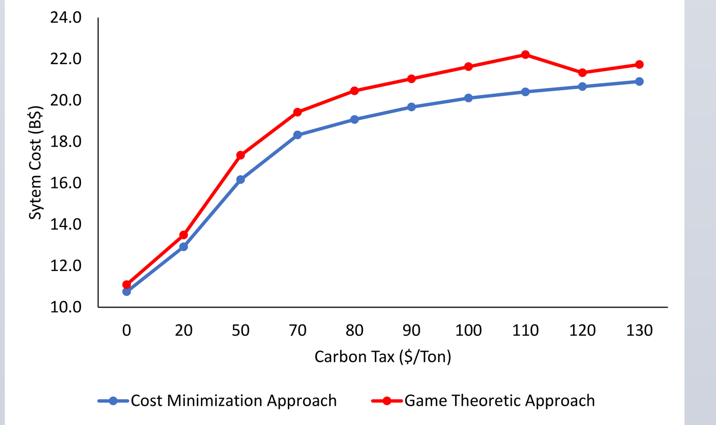

Figure 10: Total System Cost: Cost Minimization approach vs. Game Theoretic approach

CONCLUSIONS

•Strategic investment behavior changes the response to carbon taxes and affects the capacity mix in the system.

•Firms invest in a portfolio of investment technologies such as they require expensive units because they want higher electricity prices.

•Strategic investment behavior leads to higher emissions under low or high carbon taxes.

FUTURE RESEARCH

•Extend the analysis in this work by considering several ownership structures, congestion in the system, and a higher number of strategic investors.

•Include carbon tax policy uncertainty in the analysis.

•Apply the Game Theoretic approach to assess an emissions cap policy.

REFERENCES

[1] FERC, "Federal Energy Regulatory Commision," [Online]. Available: https://www.ferc.gov/industries/electric/indus-act/rto.asp.

[2] F. A. Wolak, "Measuring unilateral market power in wholesale electricity markets: the California market, 1998-2000," American Economic Review, vol. 93, no. 2, pp. 425--430, 2003.

[3] S. Borenstein, J. Bushnell and C. R. Knittel, "Market power in electricity markets: Beyond concentration measures," The Energy Journal, vol. 20, no. 4, 1999.

[4] S. J. Kazempour, A. J. Conejo and C. Ruiz, "Strategic generation investment using a complementarity approach," IEEE Transactions on Power Systems, vol. 26, no. 2, pp. 940-948, 2011.