Risk Aversion and CO_2 Regulatory Uncertainty in Power Generation Investment: Policy and Modeling Implications

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Introduction

We examine the problem of risk-averse investors facing a need to expand electricity generation capacity when they anticipate regulation of carbon dioxide emissions in the future but do not know if or when it will be passed. Regulation of the sector to protect the global climate seems likely at some point in the U.S., and anticipated costs are large relative to past regulatory interventions. We allow investors to anticipate different kinds of policies, and we consider the implications of their investment choices for operating outcomes in the presence and absence of the anticipated regulation. Numerical results from our stochastic two-stage equilibrium model suggest that in the presence of risk aversion, some kinds of carbon regulations will introduce perverse incentives favoring investment in dirty generation technology. The choice between a grandfathered permit system and an auctioned permit system has implications for efficiency and costs as well as distributional effects.

Investments in generation capacity have long lasting consequences for costs and emissions. The median coal-fired generation facility in the United States is over forty years old (Energy Information Agency, 2005). There are significant fixed costs to building capacity, and switching a particular plant from one type of fuel to another is usually expensive or impractical. Risk is increasingly important in this setting, and thus analyses that assume certainty (or the ability to switch from one stream of annualized power plant costs to another at zero or low cost) can be misleading. Financial hedges in this setting are also less available due to difficulties in the credit markets and investor reluctance to insure firms against downside risks that are likely to correlate with significant economic costs and to affect most firms in this setting simultaneously (e.g., Brown 2008, Lohr NYT 2006, Johnson 2008).

In particular, risk-averse decision makers facing uncertain regulation may make investment choices that lead to a persistently inefficient generation mix for the decades ahead. Reinelt and Keith (2007) find that the "interaction of regulatory uncertainty with irreversible investment raises the social cost of carbon abatement by as much as 50%" in this setting with risk neutral investors. Delay can lead to investment in dirty technology in hopes that future grandfathering of facilities or permits will favor existing coal plants, or to support lobbying efforts designed to minimize regulation. This overinvestment is socially suboptimal and in some cases suboptimal for business interests relative to a scenario with *either* regulation or no regulation with certainty, especially if rent-seeking costs are significant. Most policy models of the sector are unable to incorporate optionality and irreversible investments in differing technologies and risk aversion, and thus can fail to predict firm responses to actual or anticipated regulation. We examine the consequences for optimal policy outcomes of incorporating risk and uncertainty in a simple two-stage stochastic equilibrium model and consider the implications for the broader policy debate and associated modeling efforts.

The two-stage model considers investments by two types of firms, one building highly polluting but low variable cost capacity (coal-fired plants), and the other building low polluting but high variable cost capacity (natural gas plants). This first stage decision is made in the face of regulatory uncertainty as to whether or not carbon limits (in the form of a cap-and-trade system) will be imposed. In the second stage, the regulation is known, and a short-run market equilibrium among the players results. Price-taking behavior is assumed throughout. As expected, regardless of how the allowances are distributed in a cap-and-trade system, risk neutral firms make the same investment decisions in terms of the primal variables of capacity and output, even though different allowance distribution schemes would yield different profits under regulation. Even risk neutral investors choose an investment mix that is optimal for neither policy environment in the presence of uncertainty about the future, maximizing the expected payoff of investment strategies based on their prior beliefs about the likelihood of each regulatory regime. This raises the private and social costs of abatement, with likely negative impacts on the amount of abatement and concurrent environmental impacts. Risk averse investors hedge their bets even further.

In general, as intuition suggests, risk neutral suppliers facing possible regulation build more gas and less coal-fired generation capacity than in a business-as-usual scenario, regardless of what form the potential carbon regulation takes. Risk aversion complicates matters: if allowances are grandfathered (i.e., given away for free in a manner that is not contingent on firm decisions), risk aversion increases investment in coal and decreases it in gas relative to the risk neutral solution. However, if allowances are auctioned, the reverse is true. This result is driven by the gains from increased allocations of valuable permits to coal plants under grandfathering; under our parameterizations, coal plant profits are higher under regulation, broadly consistent with what has happened under the European Union Emissions Trading System (e.g., Chen et al., 2008). Compared to the grandfathering scheme, an auction, like a carbon tax, provides a more direct signal to follow: firms see the rise in the expected relative price of coal under regulatory uncertainty and the more risk-averse they are, the more inclined that they are to invest in less carbon-intensive generation.

While it is difficult to observe levels of risk aversion and risk management strategies empirically (see, e.g., Chetty 2006, 2007 for examples showing how consumer insurance choices are insufficient to deduce levels of consumer risk aversion), our modeling and simulation efforts suggest that modest amounts of risk that are dealt with via hedging of investments in durable physical capital will have implications for the ability of the power sector in the United States to meet regulatory goals efficiently.

In most of the literature on electricity market modeling generally as well as on carbon policy in particular, risk aversion by firms is not captured. Our broader purpose is to consider the implications of risk-fearing investors who make durable investments under uncertainty. Most of the simulation models used in policy making in this setting, e.g., NEMS (USDOE 2003) and IPM (USEPA 2004) are deterministic, considering a single regulatory scenario and perfect foresight regarding regulations, prices, and technologies. This is required due to the extreme complexity of these models; here we have simplified much that is important in policymaking to focus on the implications of risk and uncertainty in this sector in isolation.

We believe this to be important; Niemayer (2007) shows that older and dirtier coal plants are especially vulnerable to changes in carbon emissions rules over the next five to ten years, and this trend seems unlikely to change. Barbose et al. (2008) investigate the plans of utility companies in the west and shows that most of them are making choices based on some expectation of future carbon regulations at present.

There is a literature on modeling capacity investment under uncertainty with risk neutral actors; Kanudia and Loulou (1998) and Hu and Hobbs (2005) simulate choices using the stochastic MARKAL model (which assumes risk neutrality but accommodates multiple regulatory scenarios), and Zhuang and Gabriel (2008) solve the problem as a mixed complementarity problem. There is also work concerning optimal investments by individual risk averse generators in different contexts; Fleten et al (2002) and Unger (2002) consider generators who face uncertain output prices and are ‘penalized’ for net losses. Tseng (2002) and Liu (2008) evaluate optimal operations for a single company facing uncertain prices and Patiño-Echeverri (2006) considers single firm investments choices for a firm facing uncertain pricing. Such work takes price processes as exogenous, and leaves aside the question of how risk aversion might affect market equilibria.

Researchers have also considered financial hedges against risk in electricity markets. Dahlgren et al. (2003) considers ‘financial engineering’ and output price risk management in power markets, again for a single firm. Bjoran et al. (1999), Willems (2009) and Willems and Morbee (2008), building on work by Bessembinder and Lemon (2002) on forward-spot market equilibria, evaluate the role and benefits of financial hedges in the electricity sector with risk aversion, as well as varying liquidity constraints and degrees of market completeness. However that work does not consider impacts on equilibrium investments in the power sector; Ralph and Smeers (2008) present an initial attempt to do so, considering diversity of risk attitudes among investors.

We do not model the relative merits of various carbon policies in the broader economy as in, for instance, Parry (2003, 2005), who argues for taxes over grandfathering permits on the grounds that a tax offers greater transparency and the possibility of offsetting tax-interaction effects in other markets. Nonetheless, our research strengthens this conclusion by noting that anticipating a tax system spurs investment in low carbon technologies while the reverse may be true of grandfathered permits. We also do not allow for carbon policy to affect economy-wide allocations of investment in technology and labor as in Peretto (forthcoming) –

our results are an equilibrium only in energy markets.

This work also contributes to the established literature on the benefits of regulatory certainty; even risk neutral investors in durable technology do better in the certainty case, and for many outcomes they and society pay higher costs under risk aversion. Bergara et al. (1998) provide an analysis of this in the electricity sector; see also Levy and Spiller (1994), Lavey (2002), Porter and van der Linde (1995), Porter (1998), among others.

Methods and Models

We consider two approaches to a cap-and-trade scheme in which allowances are distributed either through free distribution based on some rule that is independent of future investment and operating decisions ("grandfathering") or auctioning. To be specific, if regulation is enacted, there will be an emissions cap for all generators in the region and all emission allowances are distributed by one rule or the other. The firms face uncertainty in the form of possible future regulation. We assume competitive markets throughout. We do not discuss demand growth or fuel price uncertainty, transmission and capacity markets, climate risk aversion, or consumer risk aversion in this simplified analysis. However, we do include demand variability, in the form of a distribution of demand functions over the year within the second stage (e.g., peak vs baseload demands). This distribution is known ahead of time to all market players, and is the reason why in equilibrium there is a mix of high- and low-variable cost generation technologies in the market. This assumption is standard in power market modeling.

We construct a stochastic non-linear equilibrium model with risk-averse firms to simulate the problem. Initially, investors make investment decisions – whether to invest and how much - without knowing the state of the world in the next stage. In the following period, in the absence of regulation, everything remains the same; if there is regulation, it takes one of several forms. In the cap-and-trade scenarios, the government sets a binding emissions cap for the whole market. Permits are then either grandfathered or auctioned, and the allowances can be traded among the generation firms in a competitive market.

In the investment decision process, the investors develop a portfolio of production plans for electricity production in both scenarios, given investments prior to the state of the world being revealed. We first assume a ‘No-regulation’ scenario demand and cost function. In the ‘Regulation’ scenario, the distribution of demand functions is unchanged. The distribution is represented by multiple demand periods within a year, each with its own demand curve and duration, summing up to 8760 hours. However, cost functions reflect the addition of equilibrium permit prices. Both the electricity prices and the permit price are solved by market clearing conditions. Firms must make investment choices to maximize their utility in expectation over all regulatory scenarios. Utility is a function of profit in the second stage, net of fixed costs and summed over the demand periods. (Thus, investors are assumed to be risk averse only with respect to regulatory scenarios, and not the variability of demand within the year.)

Risk attitudes are modeled using a concave utility-of-profit function as the objective of the firm. We consider the equilibrium results under varying degrees of risk aversion by varying the Arrow-Pratt coefficient in a Constant Absolute Risk Averse (CARA) utility function given by:

$$U(\pi) = m - n \cdot e^{-R\pi}, \quad for \;\; n > 0, R > 0 \tag{1}$$

Firms thus have a constant absolute risk-aversion (*R*) in total profit (*π*). Larger *R* indicates that the agent under study is more risk-averse.

The model is formulated as a stochastic equilibrium problem: suppliers maximize expected utility under a set of constraints; consumers maximize consumer surplus in each demand period in the second stage; and the markets for energy and allowances clear. As an optimization problem, the Karush-Kuhn-Tucker (KKT) conditions for each market player's optimization problem together with the market clearing conditions are gathered to define an equilibrium problem expressed as a mixed complementarity problem (MCP) (Pang et al. 1992). This allows for flexibility in the form and interaction of the constraints and is common in modeling for this policy setting (Bunn, 2004, Ventosa et al., 2005). We use the PATH solver in GAMS to find equilibria under various assumptions.

Modeling Definitions

We summarize the formulation of our stochastic equilibrium model with two risk-averse firms.[1] First we list the sets, parameters, variables and equations used in the model and then introduce the model and solutions as a MCP.

Sets:

i: Scenario indicator, denoted as '*reg*' for regulation and '*nreg*' for no regulation, respectively;

j: time period indicator (within a scenario), representing different levels of demand (e.g., peak

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[1] For convenience, we set up the problem with a gas-fired firm and a coal-fired firm; allowing firms to have a mixture of technology would not change the nature of the results.

daytime load vs. night baseload) within one-year time horizon;

k {Gas, Coal}: generation fuel type indicator, as well as firm indicator (gas-based firm or coal-based firm) in this setting, denoted as ‘g’ and ‘c’, respectively.

Parameters (all strictly positive):

P_{0ij}, Q_{0ij}: parameters for the linear demand function in scenario i, period j –

$$p_{ij} = P_{0ij} - \frac{P_{0ij}}{Q_{0ij}} \cdot d_{ij} \tag{2}$$

PR_i: probability of being in scenario i;

HR_j: hours in period j (hrs/yr);

CC_k: capacity cost for the firm using fuel k (\$/MW/yr);

MC_{ik}: variable cost for the firm using fuel k in scenario i (\$/MWh);

E_k: emission rate of fuel k (tons/MWh);

E^{cap}: Emission cap of the total market (tons/yr);

E^{gf}: Total grandfathering allowance in the market (tons/yr);

E^{gf}_k: Grandfathering allowance to the firm using fuel k (tons/yr);

Z_i: scenario indicator. $Z_i = 1$, if i = ‘regulation’ and $Z_i = 0$;

R: Arrow-Pratt risk aversion coefficient.

Primal Variables:

d_{ij}: quantity of electricity demanded in scenario i, demand period j of stage two (MW);

q_{ijk}: quantity of energy supplied in scenario i, period j by the firm using fuel k (MW);

cap_k: capacity constructed in stage 1 for plant using fuel k (MW);

$t_{reg,k}$: net emission permit purchase in the permit market in scenario '*reg*' by the firm using fuel *k* (tons/yr).

Dual Variables:

μ_{ijk}: dual variable for the capacity constraint for firm *k* in scenario *i*, period *j* ($/MW/yr);

p_{ij}: market clearing electricity price in scenario *i*, period *j* ($/MWh);

$\lambda_{reg,k}$: dual variable for the emission constraint for firm *k* ($/ton);

p^{e}_{reg}: equilibrium emission permit price under the *reg* scenario ($/ton).

Others:

π_{ik}: firm *k*'s profit in scenario *i*;

π_{k}: firm *k*'s expected profit;

U_{ik}: firm *k*'s utility in scenario *i*;

EU_{k}: firm *k*'s expected utility;

CS_{i}: consumers surplus in scenario *i*.

Below we give an example for the models used in the policy analysis framework. The model below simulates firms' investment problem when they are facing uncertainty in the carbon policy scheme: either there will be no regulations in the next stage (with probability PR_{nreg}), or a cap-and-trade carbon emission permit scheme (with probability $PR_{reg} = 1\text{-}PR_{nreg}$).

For firms:

For the firm using fuel *k*, profit in scenario *i* is defined as:

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p_{ij} - MC_{ik}) - CC_k \cdot cap_k - Z_i \cdot p^e_{reg} \cdot t_{reg,k} \tag{3}$$

Consequently, the utility is defined as:

$$U_{ik} = 1 - e^{-R \cdot \pi_{ik}} \tag{4}$$

Risk neutral firms maximize expected profit π_k,

$$Max \quad \pi_k = \sum_i PR_i \cdot \pi_{ik} \tag{5}$$

$$s.t. \quad q_{ijk} - cap_k \le 0 \qquad \forall\ i, j, k \qquad (\mu_{ijk}) \tag{6}$$

$$\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - t_{reg,k} \le E_k^{gf} \qquad (\lambda_{reg,k}) \tag{7}$$

This model format is robust in the sense that when the allowances are totally auctioned, E_k^{gf} = 0. Otherwise, any rule that free allowances are distributed between firms by can be captured by changing the parameter E_k^{gf}.

Risk-averse firms instead maximize their expected utility EU_k,

$$Max \quad U_k = \sum_i PR_i \cdot U_{ik} \tag{8}$$

$$s.t. \quad q_{ijk} - cap_k \le 0 \qquad \forall\ i, j, k \qquad (\mu_{ijk}) \tag{6}$$

$$\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - t_{reg,k} \le E_k^{gf} \qquad (\lambda_{reg,k}) \tag{7}$$

The KKT conditions associated with risk-averse firms are as follows. (The symbol ⊥ means that the two conditions are orthogonal, i.e., $0 \le x \perp f(x) \le 0$ is equivalent to $0 \le x$, $f(x) \le 0$, and $x \times \mathrm{f}(x) = 0$.)

$$0 \le q_{ijk} \perp \frac{\partial U}{\partial q_{ijk}} - \mu_{ijk} - Z_i \cdot E_k \cdot HR_j \cdot \lambda_{ik} \le 0 \Leftrightarrow$$

$$0 \le q_{ijk} \perp R \cdot PR_i \cdot e^{-R \cdot \pi_i} \cdot HR_j \cdot (p_{ij} - MC_{ik}) - \mu_{ijk} - Z_i \cdot E_k \cdot HR_j \cdot \lambda_{ik} \le 0 \qquad \forall\ i, j, k \tag{9}$$

$$0 \le cap_k \perp \frac{\partial U}{\partial cap_k} + \sum_{i,j} \mu_{ijk} \le 0 \Leftrightarrow$$

$$0 \le cap_k \perp \sum_i PR_i \cdot R \cdot e^{-R \cdot \pi_{ik}} \cdot (-CC_k) + \sum_{i,j} \mu_{ijk} \le 0 \qquad \forall\ k \tag{10}$$

$$0 \le t_{reg,k} \perp \frac{\partial U}{\partial t_{reg,k}} + \lambda_{reg,k} \le 0 \Leftrightarrow$$

$$0 \le t_{reg,k} \perp -PR_{reg} \cdot R \cdot e^{-R \cdot \pi_{reg,k}} \cdot p_{reg}^{e} + \lambda_{reg,k} \le 0 \qquad \forall\ k \qquad (11)$$

$$0 \le \mu_{ijk} \perp q_{ijk} - cap_k \le 0 \qquad \forall\ i, j, k \qquad (12)$$

$$0 \le \lambda_{reg,k} \perp \sum_j E_k \cdot HR_j \cdot q_{reg,jk} - E_k^{gf} - t_{reg,k} \le 0 \qquad \forall\ k \qquad (13)$$

Consumers maximize their surplus:

$$Max \quad CS_i = \sum_j HR_j \cdot [(P_{0ij} \cdot d_{ij} - \frac{1}{2}\frac{P_{0ij}}{Q_{0ij}} \cdot {d_{ij}}^2) - p_{ij} \cdot d_{ij}] \qquad (14)$$

$$s.t. \quad d_{ij} \ge 0 \qquad \forall\ i, j \qquad (15)$$

The consumers' KKT conditions are:

$$0 \le d_{ij} \perp P_{0ij} - \frac{P_{0ij}}{Q_{0ij}} \cdot d_{ij} - p_{ij} \le 0 \qquad \forall\ i, j \qquad (16)$$

The market clearing conditions for energy and emissions are, respectively:

$$\sum_k q_{ijk} = d_{ij} \qquad \forall\ i, j \qquad (p_{ij}) \qquad (17)$$

$$\sum_{j,k} E_k \cdot HR_j \cdot q_{reg,jk} = E^{cap} \qquad (p_{reg}^{e}) \qquad (18)$$

Analytical Results

In this section, we show that the market equilibrium prices, emissions, and generation mix are invariant with respect to the allowances allocation scheme, if firms are risk neutral. However, as the subsequent numerical results show, this is not true under risk aversion.

[Proposition 1] Assume risk-neutral firms and a competitive market where all firms are price takers in the power and permit markets. Consider three types of models:

i. Cap-and-trade policy model with auctioned allowances

ii. Cap-and-trade policy model with freely granted allowances, in which a fixed number of allowances are grandfathered (i.e., distributed independently of the firm's decisions)

iii. Carbon tax model, where carbon tax is exogenously set to the allowance price obtained from the auction-based allowance trading models (i)

Given a fixed emission cap, if the emission trade constraint is binding, the two allowance trading models (i) and (ii) yield the same equilibrium values of investment and energy production variables as well as quantities demanded and prices. That is, risk neutral firms in a cap-and-trade scheme will make the same plant expansion and operating decisions, regardless of how the emission allowances are distributed (grandfathering or auctioned) and initially allocated (different grandfathering allocation rules). However, the number of traded permits will vary and thus firms may realize different profits under different emission policies and different allocation rules even when they are risk neutral.

Further, we show that auctioned permits equilibrium (i) is in the subset of the solution sets for a carbon tax equilibrium (iii) when that tax equals the equilibrium permit price: if the solution to the tax problem is unique, model (i) and model (iii) are equivalent; if the tax solution is not unique, any permit equilibrium (i) is a tax equilibrium, but the reverse may not be true.

[Proof]:

First we develop the equilibrium conditions for risk neutral operators who either buy auctioned allowances, are given a fixed number of allowances for free, or some combination of the two approaches. We then derive the first order conditions for an equivalent carbon tax model. We shall make conclusions thereafter.

Part I: *Equivalence of (i) and (ii) in investment, energy, demand, and prices.* To obtain equilibrium conditions in a competitive market with risk neutral operators who are subject to a fixed emission cap (emission allowances are either auctioned or grandfathered for a certain amount), if the emission cap is binding, we can substitute the emissions constraint for firms (equation (7)) with an equality:

$$\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - t_{reg,k} = E_k^{gf} \qquad (\lambda_{reg,k}) \qquad (21)$$

We then simplify the model by substituting $t_{reg,k}$ into the objective, so equations (5) through (7) are simplified as:

For risk-neutral firms,

$$Max \quad \pi_k = \sum_i PR_i \cdot \left[\sum_j HR_j \cdot q_{ijk} \cdot (p_{ij} - MC_{ik}) - CC_k \cdot cap_k - Z_i \cdot p^e_{reg} \cdot (\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - E_k^{gf}) \right] (22)$$

$$s.t. \quad q_{ijk} \le cap_k \qquad \forall\ i,j,k \qquad (\mu_{ijk}) \qquad (6)$$

The associated KKT conditions are:

$$0 \le q_{ijk} \perp PR_i \cdot HR_j \cdot (p_{ij} - MC_{ik} - Z_i \cdot E_k \cdot p^e_{reg}) - \mu_{ijk} \le 0 \qquad \forall\ i,j,k \qquad (23)$$

$$0 \le cap_k \perp \sum_i PR_i \cdot (-CC_k) + \sum_{i,j} \mu_{ijk} \le 0 \qquad \forall\ k \qquad (24)$$

$$0 \le \mu_{ijk} \perp q_{ijk} - cap_k \le 0 \qquad \forall\ i,j,k \qquad (12)$$

The consumer’s condition and market clearing conditions (16)-(18) remain the same.

By substitution, we see that the primal decision variables of capacity, energy output, and quantity demanded (as well as the dual variable of price) are not a function of $E^{gf}{}_k$. In other words, whether the allowances are totally grandfathered ($E^{gf} = E^{cap}$), or auctioned ($E^{gf} = 0$), or distributed by another allocation rule, the solutions do not change. Thus models (i) and (ii) yield the same generator decisions and market prices. However, some variables, including the net emission permit purchase quantities and consequently the profits for firms in different scenarios, can differ.

Part II: Equivalence of (i) and (iii). The tax model (iii) is based upon the following definition of the firm's profit:

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p_{ij} - MC_{ik} - TAX_{ik}) - CC_k \cdot cap_k \tag{25}$$

In the risk neutral case,

$$Max \quad \pi_k = \sum_i PR_i \cdot \pi_{ik} \tag{26}$$

$$s.t. \quad q_{ijk} \leq cap_k \qquad \forall\ i, j, k \qquad\qquad (\mu_{ijk}) \tag{27}$$

The KKT condition with regard to the plant output variables then becomes:

$$0 \leq q_{ijk} \perp \frac{\partial \pi_k}{\partial q_{ijk}} - \mu_{ijk} \leq 0 \Leftrightarrow$$

$$0 \leq q_{ijk} \perp PR_i \cdot HR_j \cdot (p_{ij} - MC_{ik}) - PR_i \cdot HR_j \cdot TAX_{ik} - \mu_{ijk} \leq 0 \quad \forall\ i, j, k \tag{28}$$

The overall equilibrium problem consists of condition (28) plus conditions (24) and (12) for firms, (16) for consumers, and (17) for market clearing, which are the same as in models (i) and (ii).

In this way, models (i), (ii) and (iii) are comprised of the same sets of conditions except for one firm's condition (equation (19) vs. equation (28)); in addition, model (i) and (ii) have one more market clearing condition than model (iii) (equation (18)). Thus, if we show the equivalence of equations (23) and (28), we can conclude that all model (i) and (ii) solutions are in the subset of model (iii) solutions.

To show the equivalence of (23) and (28), it is sufficient to show the following equation holds:

$$PR_i \cdot HR_j \cdot TAX_{ik} = PR_i \cdot HR_j \cdot Z_i \cdot E_k \cdot p^e_{reg} \tag{29}$$

When the realized scenario is No-regulation, i.e., $Z_{nreg} = 0$, and $TAX_{nreg,k} = 0$, then (29) is satisfied trivially; when the scenario is Regulation, since the tax price for each fuel is set to be equivalent to the permit price, i.e., $TAX_{reg,k}(\$/MWh) = p^e_{reg}(\$/ton) \times E_k(tons/MWh)$, which is exactly what we want to show if (29) holds.

Therefore, model (i) and (ii)'s solutions are in the subset of model (iii)'s solution. In other words, model (i) and (ii)'s solution for the emission permit model also satisfies model (iii) conditions for the carbon tax model (but not the other way, if there are multiple equilibria for model (iii)). Additionally, if the solution for model (iii) is unique, then model (i), (ii) and model (iii) are equivalent, yielding the same primal variables, prices, and surpluses for all market participants. This completes the proof.

However, when we model risk averse firms, the equivalence stated in *Part I* no longer holds. Nevertheless, we can show certain equivalences between the model with auctioned emission permits (model (i)) and an equivalent carbon tax model (model (ii)).

[Proposition 2]: Assume risk-averse firms in a competitive market. In model (i) where emission permits are auctioned and model (iii) with an equivalent carbon tax, as described in Proposition 1, the *risk averse* market equilibrium solutions for model (i) are a subset of the solution set for model (iii) in terms of the primal variables and prices, and the solutions are identical when model (iii) has a unique equilibrium.

[Proof]:

We list both model (i) and model (iii)'s KKT conditions for risk averse firms. After rescaling the dual variables, we conclude that model (i) generate equilibria in terms of primal variables and prices which are a subset of model (iii)'s primal variable and price solution set.

Model (i) is formulated by equations (6) to (8). Simplifying constraint (7) and substituting it back into the objectives, as we already did in Proposition 1, we re-formulate model (i) as:

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p_{ij} - MC_{ik} - Z_i \cdot p^e_{reg} \cdot E_k) - CC_k \cdot cap_k \tag{30}$$

$$U_{ik} = 1 - e^{-R\pi_{ik}} \tag{31}$$

$$Max \quad U_k = \sum_i PR_i \cdot U_{ik} \tag{32}$$

$$s.t. \quad q_{ijk} \le cap_k \qquad \forall\ i,j,k \qquad\qquad (\mu_{ijk}) \tag{33}$$

The risk-averse firm's KKT conditions are:

$$0 \le q_{ijk} \perp \frac{\partial U_k}{\partial q_{ijk}} - \mu_{ijk} \le 0 \Leftrightarrow$$

$$0 \le q_{ijk} \perp PR_i \cdot R \cdot HR_j \cdot e^{-R\pi_{ik}} \cdot (p_{ij} - MC_{ik} - Z_i \cdot p^e_{reg} \cdot E_k) - \mu_{ijk} \le 0 \quad \forall\ i,j,k \tag{34}$$

plus conditions (10) and (12) for firms, (16) for consumers and two market clearing conditions stated in (17) and (18).

Meanwhile, model (iii) has profit formulated as in (25) and objective as in (32), and constraints as in (33). Then the KKT's associated with model (iii) are:

$$0 \le q_{ijk} \perp \frac{\partial U_k}{\partial q_{ijk}} - \mu_{ijk} \le 0 \Leftrightarrow$$

$$0 \le q_{ijk} \perp PR_i \cdot R \cdot HR_j \cdot e^{-R\pi_{ik}} \cdot (p_{ij} - MC_{ik} - TAX_{Ik}) - \mu_{ijk} \le 0 \quad \forall\ i,j,k \tag{35}$$

plus firms' conditions as stated in (10) and (12), consumers' condition as stated in (16) and one market clearing condition as in (17).

First we show the equivalence of (34) and (35). Then since model (i) has one more market clearing condition (18) than model (iii), if the emissions tax in (iii) is set equal to the emissions price in (i), any solution to model (ii) will also satisfy the equilibrium conditions in (iii), proving the proposition. This equivalence will again be reduced to show that (29) holds, which was previously shown in Proposition 1. Therefore, if model (iii) does not have multiple solutions, model (i) and (iii) are equivalent and this completes the proof.

Computational Application

To illustrate how firms with different risk attitudes will invest in the settings defined above, consider a single power market with the following characteristics:

- Scenarios: $i \in \{reg, nreg\}$. There are two scenarios – with carbon regulation (*reg*) and without regulation (*nreg*). We assume a 50:50 probability of regulation. This is broadly consistent with the results of a 2007 survey showing that 43% of U.S. energy executives anticipate the implementation of a global climate policy by 2009 (Cash 2007).
- Firm/Power plant types: $k \in \{g,c\}$. The two firms have different fuels – one only builds gas-fired combined cycle plants (*g*) firm and the other operates coal-fired generators (*c*).
- Time periods: $j = 1,2,\ldots, 4$ periods over a one-year horizon, totaling 8760hrs. Details of the time period definitions are in the appendix.
- Inverse demand: $p_{ij} = P_{0ij} - \frac{P_{0ij}}{Q_{0ij}} \cdot d_{ij}$. The demand function parameters are provided in

the appendix.

- Capacity costs: $CC_c = 140,000\$ / MW$ and $CC_g = 80,000\$ / MW$.
- Marginal costs of generation, exclusive of carbon permit costs:

  $MC_{*,c} = 40\ \$ / MWh, MC_{*,g} = 65\ \$ / MWh.$
- We assume that the gas-fired combined cycle plant emits half as much carbon dioxide per MWh as a coal-fired plant. So $E_c = 1$ *tons/MWh* and $E_g = 0.5$ *tons/MWh*.
- The emission baseline of the whole market is derived as the actual emissions (actual sales weighted by emission rates) from a ‘business-as-usual’ scenario (i.e., derived assuming 100% chance of no regulation).
- The emissions cap is set at 80% of the business as usual scenario, that is, a 20% emission cut. When the policy is to auction allowances, all emission allowances available in the market (80% from baseline) will be auctioned; in the same way, when the policy is to grandfather allowances, all the available emissions will be granted to firms for free.
- There are two ways that initial emission allowances are allocated in the grandfathering policy scheme. The first is the ‘capacity allocation’ rule: emission allowances are allocated proportional to weighted capacity in the baseline solution.

$$E_k^{gf} = \frac{E_k \cdot cap^0{}_k}{\sum_f E_f \cdot cap^0{}_f} \cdot E^{gf}, \qquad \forall k \tag{19}$$

- Alternately, under the ‘generation allocation’ rule, initial emission allowances are allocated based on baseline emissions:

$$E_k^{gf'} = \frac{\sum_j E_k \cdot q^0{}_{ijk} \cdot HR_j}{\sum_{j,f} E_f \cdot q^0{}_{ijf} \cdot HR_j} \cdot E^{gf}, \qquad \forall k \tag{20}$$

where $cap^0{}_k$, $q^0{}_{ijk}$ indicates the capacity/output decisions as solved from the business as usual/base case. Note that the resulting Egfk and Egfk' are exogenous to the choices made my firms in the stochastic market equilibria, so this is a true grandfathering scheme, not an updating scheme. The most salient difference here is that the generation-based rule gives most of the allowances to coal-fired generation, and the capacity based rule splits them more evenly.

- Utility function: $U(\pi) = m - n \cdot e^{-R \cdot \pi}$, for $n > 0, R > 0$, and π as total profit; we will choose m, n only to scale the utility value up in order to avoid numerical problems. However, in the tables, we report the value for $U(\pi) = 1 - e^{-R \cdot \pi}$ for simplicity.

Investors make capacity investment decisions without knowing the state of the world. However, they do know the nature of the possible regulation and how many initial emissions allowances will be allocated to them in the regulated state i = reg.

As shown above, the initial allocation rule will not affect the risk-neutral firms' investment and operating decisions nor market prices, but for risk-averse firms, it might. To analyze the impact of considering risk-aversion, we present a stochastic equilibrium model with three model classes:

- Initially, we assume a 100% chance of a 'business-as-usual'/ 'No-Regulation' (*nreg*) scenario only to derive baseline emissions. We formulate the equilibrium problem in the *nreg* scenario and consequently obtain the emission allowances and initial allocation plan for the cap-and-trade scenario. Note that since there is no regulatory uncertainty, the equilibrium is not affected by the risk aversion of the suppliers, so we solve a risk-neutral model.

- Secondly, we consider the scenario with firms facing certain regulation *reg*. Again, the risk-neutral and risk-averse equilibria are the same when there is a 100% chance of one particular scenario.
- We then introduce scenario uncertainty facing risk-neutral firms: the firms build capacity to maximize expected profits over possible scenarios.
- Finally, we allow risk-averse producers to maximize their expected *utilities* of profits or losses. Other than that, all conditions are the same as in the previous stage. We consider varying levels of risk-aversion and observe their effect on investment choices and other outcomes as they compare to the risk-neutral and certain cases.

Model Solutions and Discussion

A few key results are in Table 1; full solutions under different scenarios are shown in the appendix. The appended tables show the solutions for selected primal variables and prices (capacity built, demand, power prices, permit prices and so on) and other important indicators. Appended tables 2 through 4 show fuller solutions for the cap-and-trade scheme – Table 2 shows model solutions where emission allowances are auctioned; Tables 3 and 4 show solutions where emission allowances are grandfathered

Table 1: Summary of key results

		Deterministic Equilibria		Stochastic - Risk Neutral		Stochastic - Risk Averse	
		Baseline	Regulation	No Regulation	Regulation	No Regulation	Regulation
Gas Capacity MW	Auction	1890.5	2329.1	1973.3	1973.3	2201.0	2201.0
	GF (Generation Allocation)	1890.5	2329.1	1973.3	1973.3	1849.9	1849.9
	GF (Capacity Allocation)	1890.5	2329.1	1973.3	1973.3	1941.2	1941.2
Coal Capacity MW	Auction	1146..00	608.0	992.3	992.3	762.6	762.6
	GF (Generation Allocation)	1146.0	608.0	992.3	992.3	1117.7	1117.7
	GF (Capacity Allocation)	1146.0	608.0	992.3	992.3	1050.7	1050.7
Demand Weighted Price ($/MWh)	Auction	74.9	107.3	81.9	114.7	88.5	114.8
	GF (Generation Allocation)	74.9	107.3	81.9	114.7	76.9	114.7
	GF (Capacity Allocation)	74.9	107.3	81.9	114.7	79.5	114.7
Gas supplied Million MWh	Auction	1.1	3.9	1.6	3.9	3.0	3.9
	GF (Generation Allocation)	1.1	3.9	1.6	3.9	1.1	3.9
	GF (Capacity Allocation)	1.1	3.9	1.6	3.9	1.3	3.9
Coal Supplied Million MWh	Auction	8.6	5.4	8.0	5.4	6.6	5.4
	GF (Generation Allocation)	8.6	5.4	8.0	5.4	8.5	5.4
	GF (Capacity Allocation)	8.6	5.4	8.0	5.4	8.3	5.4
Gas Emissions Million T/yr	Auction	5.3	2.0	7.9	2.0	1.5	2.0
	GF (Generation Allocation)	5.3	2.0	7.9	2.0	5.6	2.0
	GF (Capacity Allocation)	5.3	2.0	7.9	2.0	6.7	2.0
Coal Emissions Million T/yr	Auction	8.6	5.3	8.0	5.4	6.6	5.4
	GF (Generation Allocation)	8.6	5.3	8.0	5.4	8.5	5.4
	GF (Capacity Allocation)	8.6	5.3	8.0	5.4	8.3	5.4
CO2 Permit Price	Auction	--	35.0	--	50.0	--	50.0
	GF (Generation Allocation)	--	35.0	--	50.0	--	50.0
	GF (Capacity Allocation)	--	35.0	--	50.0	--	50.0
Gas-fired Profit (million $/yr)	Auction	0.0	0.0	4.9	-4.9	5.7	-5.4
	GF (Generation Allocation)	0.0	0.0	4.9	16.4	4.5	16.6
	GF (Capacity Allocation)	0.0	0.0	4.9	161.0	3.1	159.0
Coal-fired Profit (million $/yr)	Auction	0.0	0.0	62.0	-62.0	99.2	-47.6
	GF (Generation Allocation)	0.0	0.0	62.0	283.0	19.5	275.0
	GF (Capacity Allocation)	0.0	0.0	62.0	139.0	42.0	134.0
Total Emissions per Output** (tons/MW)	Auction	1.0	0.8	0.9	0.8	0.8	0.8
	GF (Generation Allocation)	1.0	0.8	0.9	0.8	0.9	0.8
	GF (Capacity Allocation)	1.0	0.8	0.9	0.8	0.9	0.8
Average Generation Cost ($/MWh)	Auction	74.9	107.3	75.0	122.0	77.5	120.5
	GF (Generation Allocation)	74.9	79.9	75.0	82.5	74.4	83.3
	GF (Capacity Allocation)	74.9	79.9	75.0	82.5	74.9	83.1
Average Variable Generation Cost ($/MWh)	Auction	42.7	78.1	44.1	90.0	47.9	90.0
	GF (Generation Allocation)	42.7	50.7	44.1	50.6	42.9	50.6
	GF (Capacity Allocation)	42.7	50.7	44.1	50.6	43.5	50.6
Average Fixed Generation Cost ($/MWh)	Auction	32.2	29.2	30.9	32.0	29.6	30.5
	GF (Generation Allocation)	32.2	29.2	30.9	32.0	31.5	32.8
	GF (Capacity Allocation)	32.2	29.2	30.9	32.0	31.4	32.6

*Risk averse results are for the middle parameterization of risk; column 6 in the appendix tables

1. Uncertainty and risk neutrality

Initially we solve for the market's baseline emission level; we then define the total emission cap as 80% of that level.[2] This case corresponds to Column 2 from tables 2 through 4. At baseline, the gas plant installs 1890 MW of capacity, the coal plant installs 1146 MW of

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[2] The results shown are all for a 20% reduction in emissions; we also performed the analysis for a 50% reduction, with results showing similar trends but, as would be expected, of greater magnitude. These are available from the authors upon request, but are not reported as we feel that the 20% results are more relevant to the current policy discourse. Risk aversion with regards to fixed capital investments should reflect the expected regulatory timeline, and a 20% reduction within the lifetime of a new power plant is certainly plausible in the United States at present.

capacity and they serve demand ranging from 595-3036 MW. In the baseline setting, the gas plant operates at full capacity (1890 MW) in peak demand periods and shuts down when demand is low, because gas-turbine generated power is relatively more expensive than coal-fired generated power. The coal plant runs at full capacity (1146 MW) for the peak, and provides all the power when demand is less than or equal to its capacity. With the emission factors we assumed, the gas plant has a baseline of 0.53 million tons/yr (=$\sum_j q_{nreg,j,g}$ MW * HR_j hrs/yr * 0.5 ton/MWh). Similarly, the coal plant has a baseline of 8.63 million tons/year (=$\sum_j q_{nreg,,j,c}$ MW * HR_j hrs/yr * 1 ton/MWh). Thus, the total CO_2 emission baseline is 9.16 million tons/yr.

If regulation will occur with certainty, investment in gas generation increases and in coal decreases, with an equilibrium installed capacity of 2329 MW and 608 MW, respectively. Emissions intensity falls 17%, and total emissions fall to 7.33 million tons/year. Total quantity of power supplied drops by about 4% relative to the baseline as prices rise.

For risk-neutral suppliers facing uncertainty, we observe the following trends: compared to the no regulation baseline, if investors know the regulation will be implemented with certainty, the gas plant increases its capacity and investments in coal-fired capacity decline. If regulation only has a 50% chance of occurrence, both changes are moderated. This finding is consistent with basic economic intuition regarding uncertainty and holds for regulations that impose a permit auction and for those that grandfather permits.

As this is a long run equilibrium problem without scale economies, risk neutral firms realize zero expected profits in the auction model. Thus, when the emissions cap is 80% of the baseline emissions, in the auction case, the gas firm sees a profit of 4.93 million $/yr in the no-regulation scenario and -4.93 million $/yr in the regulation scenario; the coal firm sees a profit of 62.0 million $/yr in the no-regulation scenario and -62.0 million$/yr in the regulation scenario. Both lose money under regulation because power prices have not risen enough to cover the expense of allowances.

However, when the government allocates allowances for free to risk neutral firms, expected profits are positive and equal to the value of the free allowances. Consider the risk neutral case: the gas firm earns 4.93 M$/yr in the no-regulation scenario and 16.4 million dollars in the regulation scenario; the coal company earns 62 million dollars in the no-regulation scenario and 283 million dollars in the regulation scenario. The total expected profit of the two plants is thus 183 million dollars. The total expected economic rent associated with the free allowances is also 183 million $/yr (=7.33 million ton/yr * 50$/ton * 0.5, with 0.5 the probability of being in regulation).

Since regardless of how free allowances are allocated, risk-neutral firms facing the same emissions cap make the same investment and operating decisions, the same quantities supplied and power prices emerge in equilibrium.. When the emissions cap is 80% of the baseline total emissions, risk neutral firms facing regulatory uncertainty will make the following investment decisions: the gas firm builds a capacity of 1973 MW and the coal firm builds a capacity of 992 MW. The demand weighted power price is 81.9 $/MWh if the regulation is not implemented and 114.7 $/MWh if it is. However, there are differences in the net permits purchased by each firm and their individual profits under regulation for alternative allowance distribution schemes. For example, the coal firm makes a loss under regulation with auctioned permits, but earns profits if allowances are grandfathered. This difference in profits will affect the equilibrium investments and prices for risk averse investors, described below.

2. Adding risk aversion

In contrast, when firms are risk averse, how emission allowances are allocated affects investment decisions under regulatory uncertainty. When all the allowances are auctioned, risk-averse firms build more (relatively clean) gas capacity and less (relatively dirty) coal capacity than risk-neutral firms. This effect increases as the firms become more risk-averse (Figure 1 and appended Table 2). However, the reverse happens if allowances are grandfathered under either of the proposed rules (Figures 2 and 3 and appended Tables 3 and 4)—the gas firm builds a smaller capacity plant and the coal plant increases capacity. Thus, the effect of risk aversion is ambiguous, interacting with the choice of how allowances are to be distributed. Although the focus of political debate over whether allowances should be granted freely or auctioned has been on who gets the resulting economic rents, if risk aversion is important, there are also implications for generation mix, costs, and even, as discussed below, emissions.

We find that the average energy price (demand weighted) in the "Regulation" scenario rises when the allowances are auctioned, but drops when the allowances are grandfathered (regardless of allocation rule) as firms become more and more risk averse, though the average energy price in the "No-regulation" scenario doesn't seem to be very sensitive to the allocation policy since total output doesn't change – generation is simply moved from one plant to another. In contrast, in the regulated scenario, the cap can only be met with the demand reductions associated with higher prices. For the relatively mild emissions reduction shown here, the permit price is not very sensitive to either risk attitudes or emission allocation rules. However, we do observe permit price sensitivity for a more aggressive emission reduction (50% emission cap). Figures 1-3 show capacity decisions under different levels of risk aversion in investors facing a possible 80% emissions cap.

This interaction between risk aversion and investment choices can be explained as follows. Generally, the effect of a concave (risk-averse) utility function is to put more relative weight on the ‘bad’ (less profitable) scenarios in the decision process. The greater the degree of risk aversion, the more weight placed on the worst scenario and, as a result, the more the firm’s investment choice will resemble the decision made if the ‘bad’ scenario is certain. This trend is indicated by the arrows in figures 1-3. What the ‘bad’ scenario will be depends on the specific policies under consideration. For example, when emission allowances are allocated for free (grandfathering), firms receive a ‘free’ asset – the value of emission permit - and profits are higher than under no regulation. In this case, firms view ‘regulation’ as a ‘good’ scenario and ‘no-regulation’ as a ‘bad’ one. Thus, under grandfathering increased risk aversion will tend to move firms’ decisions towards the pure ‘no-regulation’ case, increasing coal capacity. However, when allowances are auctioned, the government is allocated the new asset instead of generation firms, and the cost of production is increased under regulation, making the regulated scenario the ‘bad’ one. As energy prices do not increase enough to compensate, firms are worse off under regulation with auctioned permits, and risk aversion causes them to hedge against that eventuality in their capacity expansion choices by investing in the relatively clean technology.

Figure 1.

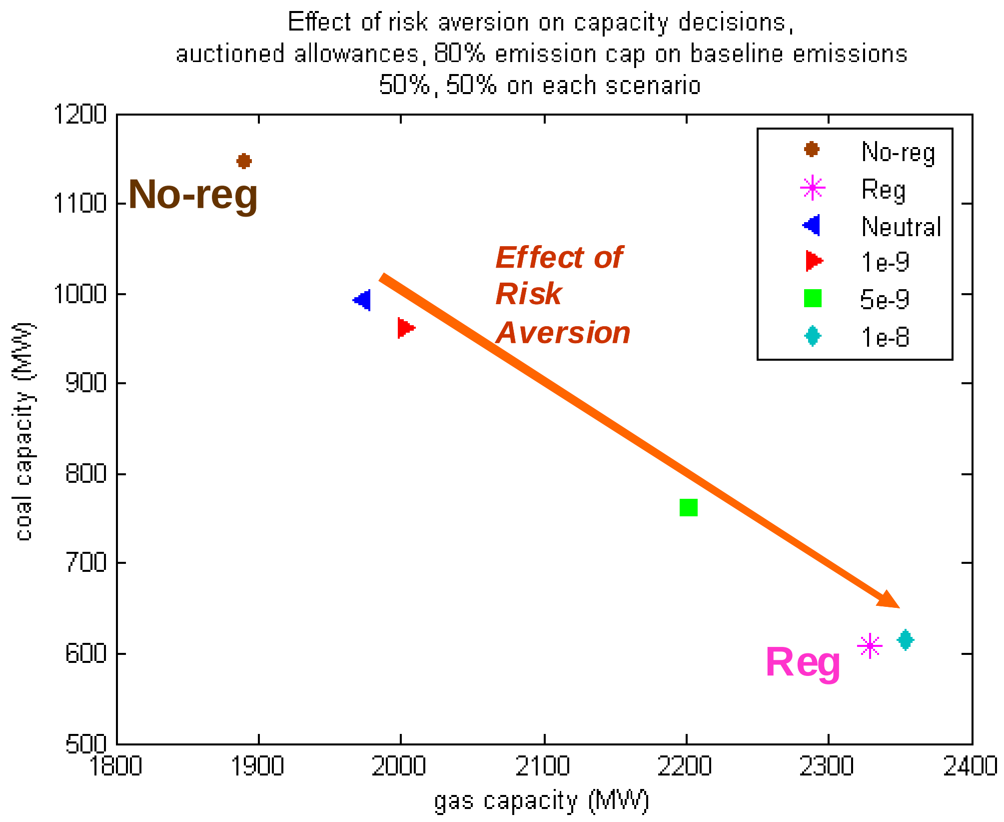

Effect of risk aversion on capacity decisions,
auctioned allowances, 80% emission cap on baseline emissions
50%, 50% on each scenario
coal capacity (MW)
gas capacity (MW)
1200
1100
1000
900
800
700
600
500
1800
1900
2000
2100
2200
2300
2400
No-reg
Effect of Risk Aversion
Reg
No-reg
Reg
Neutral
1e-9
5e-9
1e-8

Figure 2

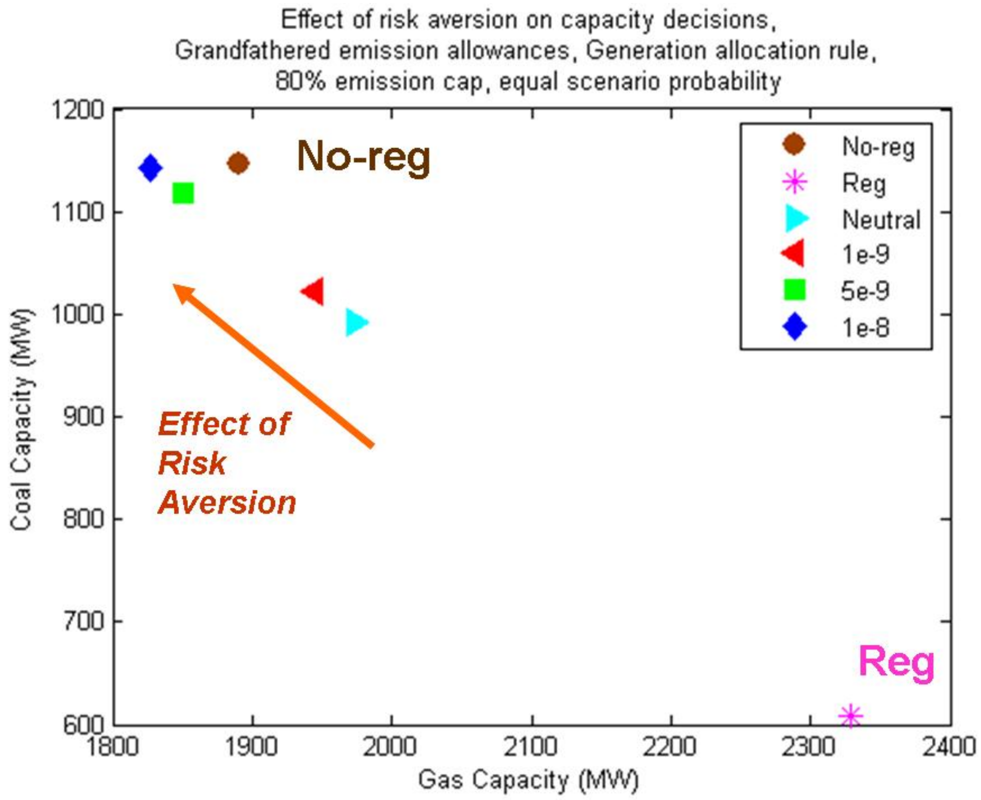
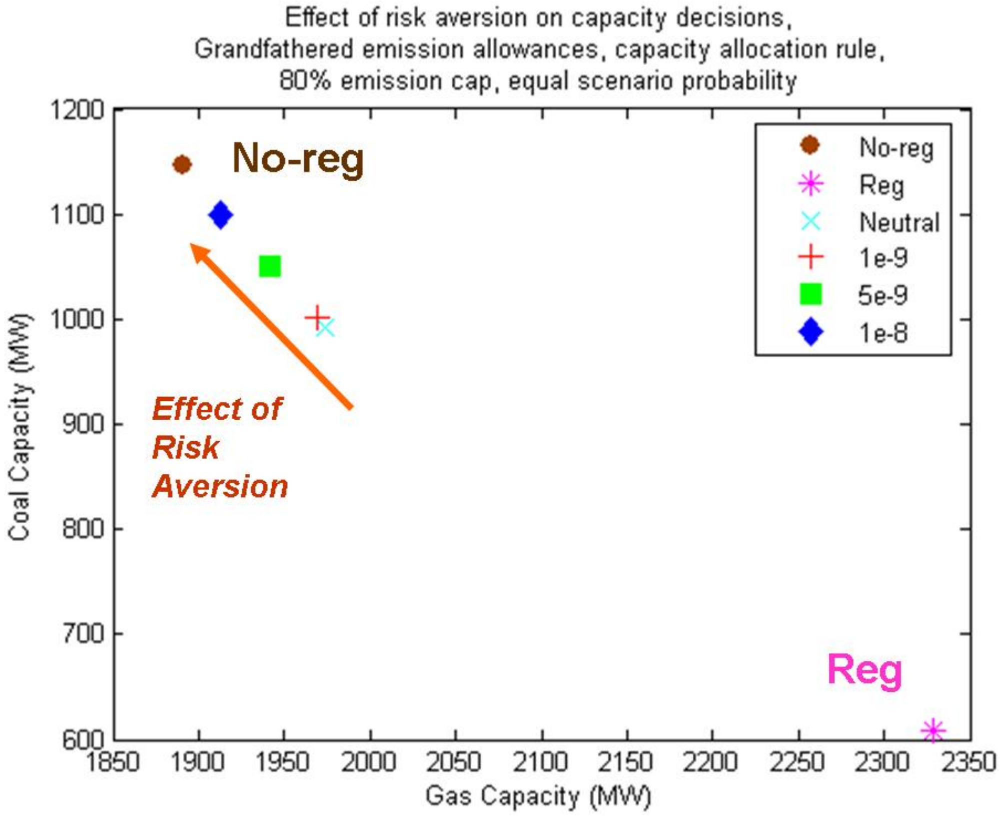

Effect of risk aversion on capacity decisions,
Grandfathered emission allowances, Generation allocation rule,
80% emission cap, equal scenario probability
Coal Capacity (MW)
Gas Capacity (MW)
1200
1100
1000
900
800
700
600
1800
1900
2000
2100
2200
2300
2400
No-reg
Effect of Risk Aversion
Reg
No-reg
Reg
Neutral
1e-9
5e-9
1e-8

Figure 3



The permit market is competitive, so the permit price equals the marginal cost of control. In this case, this is the cost of reducing emissions by one additional ton by switching from coal to gas generation. In appended Table 3 Column 6, (the “moderate” risk aversion case), the permit price is 50$/ton of emissions. If an emissions reduction was to be achieved by lowering demand, that could occur, for instance, by raising price slightly in the last (lowest demand) period. Price at that time is $90/MWh, and the marginal source of energy is coal, whose fuel cost is $40; so the loss of willingness-to-pay (net of fuel savings) is $50, which equals the price of emissions allowances. This allowance price is also consistent with a pure supply-side emissions reduction strategy of substituting gas for coal: reducing emissions by 1 ton under a constant quantity demanded would be accomplished by increasing generation by gas by 2 MWh and lowering generation by coal by an equal amount, lowering emissions by 2 MWh*(1

- 0.5 tons/MWh) = 1 ton. This would increase fuel costs by 2 MWh*(65 $/MWh – 40 $/MWh) = $50/ton, which again is the allowance price.

The change in capacity mix due to risk aversion affects not only expected costs in the stochastic equilibria, but also emissions in the no-regulation scenario in those equilibria.. (Of course, emissions in the regulated scenario are unaffected by definition since the same cap is assumed for all regulated cases.) In the auctioned allowances case, because risk aversion decreases the amount of coal capacity and increases gas capacity, a cleaner set of generation capacity is available in the no-regulation scenario than under risk neutrality, and emissions decrease. In the stochastic equilibria under risk neutrality with regulatory uncertainty, realized no-regulation emissions are 96% of the emissions at the deterministic baseline; as risk aversion is introduced and increased, no-regulation emissions drop to between 81 and 95% of the base case as gas capacity increases. The reverse happens if allowances are given away; as risk aversion increases, the installed capacity mix becomes dirtier, and so emissions increase relative to the risk neutral case. Emissions under risk aversion with the emissions-based allocation rule range from 97 to ~100% of baseline emissions when the anticipated policy is not realized in the second stage; the range is from 97 to 99% under the capacity rule. Thus, the interaction of risk aversion and allowance distribution via grandfathering or auction has not only cost implications but also emissions effects in the period prior to implementation of a policy program, though the exact allocation rule for grandfathered allowances has relatively small impacts in the parameterization used for our analysis.

Interpretation of the degree of risk aversion

Are the risk aversion coefficients considered in this example relevant to current policy choices? Measuring the degree of risk aversion in this setting is not trivial; in general it is difficult to observe participation in financial hedging markets, the degree to which long-term fuel contracts influence investor choices, or the individual risk-taking characteristics of decision makers. Further, Babcock (1993) discusses the difficulty of interpreting (or providing intuition for) the degree of risk aversion based on the CARA coefficient. Rather than attempt to empirically estimate risk tolerance of investors in this setting, we consider the implicit weights placed on the 'bad' outcome by our modeled investors under the given scenarios and argue that they do not seem unreasonable.

In expected utility theory, the certainty equivalent is the amount of payoff that an agent would have to receive to be indifferent between that payoff and a given gamble. For a risk-averse agent, the certainty equivalent is less than the expected value of the gamble because the agent dislikes uncertainty. And as a result, the certainty equivalent of a given gamble will differ among agents of different levels of risk aversion for any gamble. Since we know each scenario's realized payoff, we can view the certainty equivalent as a weighted payoff of different scenarios, which will of course be different from the probability assigned to the scenarios.

For example, in the cap-and-trade scenario with auctioned allowances, the gas firm with a risk aversion coefficient of 5×10^{-9} (Column 6 from appended Table 2) sees a profit of 5.65 million $/yr in the absence of carbon regulations; meanwhile it will lose 5.35 million $/yr if the regulation is implemented. The certainty equivalent for him to accept this investment gamble is 0.76 million $/yr – this is **equivalent to a weight of 49% on the profit in**

“No-regulation” scenario and 51% on the profit from “Regulation” scenarios. {lin – throw in a sentence showing a sample calculation here} Compared to the risk-neutral case, where we simply weight profits by the probability of being in each scenario, this risk-aversion coefficient reflects a little more weighting on the “bad” or “regulation” scenario to mitigate risk.

The more risk-averse the firm is, the more curvature the utility function has. For example, under 80% baseline emission cap, with allowances grandfathered using the emissions distribution rule, consider the solution for firms with $r = 5 \times 10^{-9}$ (appended Table 3, Column 6): the gas firm earns 4.49 million \$ (U = 0.022) in the ‘No-regulation’ scenario and 16.6 million \$ (U = 0.079) in the ‘Regulation’ scenario. The expected utility is U = 0.051, which could also be interpreted as 10.4million \$ in profit given the risk aversion coefficient. Thus we can calculate that the gas firm is putting **51.2% weight on the ‘No-regulation’/bad scenario and 48.8% on the ‘Regulation’/good scenario**. In the same way, if we check the weights that the coal firm implicitly puts on each scenario, we find that the **coal plant is putting a weight of 65% on the ‘No-regulation’ scenario and 35% on the ‘Regulation’ scenario.**

We can do the same ‘scenario weight’ calculation for firms with more risk-aversion. For example, in Column 7 of table 3, **the gas firm puts a weight of 51.6% on the bad (No-regulation) scenario and the coal firm puts 76.7% on the bad scenario**. The weights for both firms are different than those derived from Column 6 of table 3. The difference is that, as the firms become more and more risk averse, they are putting more weight on the “bad” scenario: the gas firm weights the bad scenario from 51.2% to 51.6% and the coal firm weights it from 65% to 76.7% as the risk aversion coefficient raises from 5e-9 to 1e-8.

Conclusions

For risk averse generators, the least profitable scenario is more heavily weighted than under risk neutrality. This makes capacity and cost outcomes sensitive to the allocation scheme for allowances, since the choice of allocation policy determines whether the regulation or no-regulation scenario is more profitable. While risk neutral firms will make the same investment decision in terms of primal variables (capacities, supplies, prices, demands), regardless of how the emission allowances are distributed (grandfathering or auctioned) and initially allocated (different allocation rules), risk averse firms will not: if carbon is taxed or allowances are auctioned, investment in clean generation increases, while if allowances are allocated to producers for free, the reverse happens as generators position themselves for the windfall associated with free permits. These trends occur under a 20% emissions cut and persist with a 50% reduction, though in a policy context investment flexibility is more likely over the time scales discussed to achieve 50% emission reductions – few proposed policies call for 50% reductions over the licensed or accounting life of capacity installed today.

With risk aversion, emissions in the ‘no regulation’ scenario are lower for auctioned permits and higher with grandfathering. Consumer prices under regulation are not very sensitive to distribution/allocation of permits in the regulated scenario; however, if the proposed regulation is not implemented, consumer prices rise with risk aversion if an auction is anticipated and fall if grandfathering is anticipated. Complete social welfare calculations are not possible without valuing avoided climate damages (and damages associated with other pollutants for each technology), but these results imply losses of productive and allocative efficiency in power markets.

BH In Europe and the US, there has been surprise that people are still building coal plants in the face of pending regulation – could this phenomenon be interpreted in light of our results? (do we have a handy cite for this?)

This finding has policy implications: allocation schemes don't just determine who gets rents from creating emissions rights. Certainty about the nature of a proposed regulation may be as important as certainty that carbon will be priced – either can have persistent impacts on the costs of compliance when a rule is passed. Our preliminary work in this area suggests that allowing producers to influence the size of the cap (by having current choices affect the baseline) seems to intensify these trends. We speculate that a regulatory threat to restrict CO2 not likely to have an impact ala Acutt et al. (2001), who found that a credible regulatory threat may itself induce compliance to avoid regulation; in this setting, such a case would appear to require very specific rules about the nature of the threatened regulation (e.g. a tax rather than a cap and trade system). Additionally, if political considerations make regulators unable or unwilling to impose carbon dioxide restrictions without helping dirty sectors, it might be preferable to find ways to rebate the funds raised from an auction in ways that do not encourage carbon-intensive generation investment.

More generally, we find that a failure to consider risk and risk aversion may bias models of this sector and others, especially where durable capital investments limit adjustment options. Ongoing work is needed to determine how risk aversion might be incorporated in large-scale policy models. Defensible heuristics or efforts to estimate the degree of risk aversion empirically might strengthen future modeling efforts. Further, this work abstracts from known important features of the policy setting. How might market power, uncertainty about the level of a cap, uncertainty about nature of regulation, renewable standards and uncertainty about fuel and output prices affect investment? What about leakage across regulatory boundaries, or engineering risks, eg grid reliability? A more detailed specification of the plant itself could enable consideration of plant lifecycles and scale effects in technology – this would ideally include the dynamics of investment choices when the investor already owns heterogenous capital stock for electricity generation; the choice of when to retire old capital so as to delay decision making under uncertainty is likely to be important in this setting.

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Appended Tables.

Table 1: Multi-period demand function parameters

The inverse demand function in the cap-and-trade scheme, multi-period definition model is defined as: $P_{ij} = PO_{ij} - \frac{PO_{ij}}{QO_{ij}} D_{ij}$, where the value for the parameters PO_{ij}'s and QO_{ij}'s are defined as:

PO_{ij} = 1000;

QO_{ij} as:

QO_{i1}	QO_{i2}	QO_{i3}	QO_{i4}	QO_{i5}	QO_{i6}	QO_{i7}	QO_{i8}
15000	3500	2600	2200	2000	1750	1650	1550
QO_{i9}	$QO_{i,10}$	$QO_{i,11}$	$QO_{i,12}$	$QO_{i,13}$	$QO_{i,14}$	$QO_{i,15}$	$QO_{i.16}$
1450	1375	1200	1250	1200	1160	1120	1080
$QO_{i,17}$	$QO_{i,18}$	$QO_{i,19}$	$QO_{i,20}$	$QO_{i,21}$	$QO_{i,22}$	$QO_{i,23}$	$QO_{i,24}$
1050	1010	980	940	900	850	780	620

Table 2: Example of solutions found with 80% emission cap,
Auctioned Allowances[3] in a competitive market, multi-period model

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[3] To consider scaling problem, we use a scaling factor of 10,000,000 throughout the programming. In other words, the utility function in programming is U = 100,000,000 - 100,000,000 * e^{-rx}. But for simplicity, I just showed the solution values for the

Column 1	2	3	4	5	6	7
risk-aver coeff R:	Neutral	Neutral	Neutral	1e-9	5e-9	1e-8
Free allowances *l*	Base*	Reg 80%**	80%***	80%***	80%***	80%***
Capacity_Gas (MW)	1890.49	2329.12	1973.29	2002.75	2200.99	2353.53
Capacity_Coal (MW)	1146.00	608.04	992.25	962.44	762.60	614.61
Price_nreg, (pk1 vs. opk23) ($/MWh)	797.57	--	802.30	802.32	802.43	802.12
	40	--	40	40	40	40
Price_reg (pk1 vs. opk23) ($/MWh)	--	804.19	802.30	802.32	802.43	802.12
	--	75	90	90	90	85.71
Price demand weighted_nreg ($/MWh)	74.90	--	81.94	82.84	88.46	89.46
Price demand weighted_reg ($/MWh)	--	107.26	114.74	114.75	114.75	112.57
Demand_nreg (pk1 vs. opk23) (MWh)	3036.49	--	2965.54	2965.19	2963.59	2968.14
	595.20	--	595.20	595.20	595.20	595.20
Demand_reg (pk1 vs. opk23) (MWh)	--	2937.16	2965.54	2965.19	2963.59	2968.14
	--	573.50	564.20	564.20	564.20	566.860
Output_nreg, Gas (pk1 vs. opk23) (MWh)	1890.49	--	1973.29	2002.75	2200.99	2353.53
	0	--	0	0	0	0
Output_nreg, Coal (pk1 vs. opk23) (MWh)	1146.00	--	992.25	962.44	762.60	614.61
	595.20	--	595.20	595.20	595.20	595.20
Output_reg, Gas (pk1 vs. opk23) (MWh)	--	2329.12	1973.29	2002.75	2200.99	2353.53
	--	0	145.54	564.20	0	0
Output_reg, Coal (pk1 vs. opk23) (MWh)	--	608.04	992.25	962.44	762.60	641.61
	--	573.50	418.66	0	564.20	566.86
Net permit trade_Gas (million tons/yr)	--	2.03	1.96	1.96	1.96	1.98
Net permit trade_Coal (million tons/yr)	--	5.30	5.37	5.37	5.37e6	5.35

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basic function $U = 1 - e^{-rx}$ here.

* This column, labeled “Base”, indicates that the model assumes the scenario will be ‘No-regulation’ for sure, that is, the ‘business-as-usual’ scenario.

** This column, labeled “Reg *l* %”, indicates that the model assumes ‘Regulation’ scenario for sure, with *l* % emission cap. And it applies to other tables as well.

*** These columns, labeled “*l* %”, are all for models that consider scenario uncertainty and the regulation scenario will have *l* % emission cap. And it applies to other tables as well.

Column 1	2	3	4	5	6	7
risk-aver coeff R:	Neutral	Neutral	Neutral	1e-9	5e-9	1e-8
Free allowances *l*	Base*	Reg 80%**	80%***	80%***	80%***	80%***
Permit price ($/ton)	--	35.00	50	50	50	45.71
Profit_nreg, Gas (million $/yr)	0	--	4.93	5.03	5.65e6	5.67
Profit_nreg,Coal (million $/yr)	0	--	62	68.4	9.92e7	85.7
Profit_reg, Gas (million $/yr)	--	0	-4.93	-4.98	-5.35e6	-5.09
Profit_reg, Coal (million $/yr)	--	0	-62.0	-60.1	-47.6	-27.7
Utility_nreg, Gas	--	--	--	0.005	0.028	0.055
Utility_nreg, Coal	--	--	--	0.066	0.391	0.583
Utility_reg, Gas	--	--	--	-0.005	-0.027	-0.052
Utility_reg, Coal	--	--	--	-0.062	-0.269	-0.319
Expected utility Gas	--	--	--	0	0	0.001
Expected utility Coal	--	--	--	0.002	0.061	0.132
Certainty Equivalent_Gas (thousand $/yr)	--	--	--	12.52	75.66	144.00
Certainty Equivalent_Coal (million $/yr)	--	--	--	2.06	12.6	14.2
Emissions Nreg Gas (million ton/yr)	0.53	--	0.79	0.86	0.15	2.09
Emissions Nreg Coal (million ton/yr)	8.63	--	8.03	7.88	6.55	5.37
Emissions Reg Gas (million ton/yr)	--	2.03	1.96	1.96	1.96	1.98
Emissions Reg Coal (million ton/yr)	--	5.30	5.37	5.37	5.37	5.35
Total Emissions_nreg (million ton/yr)	9.16	--	8.82	8.74	8.05	7.45
Total emissions_reg (million ton/yr)	--	7.33	7.33	7.33	7.33	7.33
Producer Surplus*[4]_nreg	0	--	66.9	73.4	104.8	93.2

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[4] * Producer Surplus in scenario i here is defined as the total profits of all operators in scenario i.
** Social welfare in scenario i is defined as the sum of producer surplus, consumer surplus, and government surplus.

Column 1	2	3	4	5	6	7
risk-aver coeff R:	Neutral	Neutral	Neutral	1e-9	5e-9	1e-8
Free allowances *l*	Base*	Reg 80%**	80%***	80%***	80%***	80%***
(million $/yr)						
Producer Surplus_reg (million $/yr)	--	0.017	-66.9	-65.1	-53.0	-32.8
Consumer Surplus_nreg (billion $/yr)	4.48	--	4.41	4.40	4.35	4.34
Consumer Surplus_reg (billion $/yr)	--	4.18	4.11	4.11	4.11	4.13
Social Welfare**_nreg (billion $/yr)	4.48	--	4.48	4.48	4.46	4.44
Social Welfare**_reg (billion $/yr)	--	4.43	4.41	4.41	4.42	4.43

Table 3: Example of solutions found with 80% Cap,
Grandfathered emission allowances (Generation allocation rule)
in a competitive market, multi periods model

Column 1	2	3	4	5	6	7
risk-aver coeff r:	Neutral	Neutral**	Neutral	1e-9	5e-9	1e-8
Free allowances *l*	Base	Reg 80%	80%	80%	80%	80%
Capacity_Gas (MW)	1890.49	2329.12	1973.29	1944.61	1849.94	1826.93
Capacity_Coal (MW)	1146.00	608.04	992.25	1021.34	1117.74	1142.93
Price_nreg, (pk1 vs. opk23) ($/MWh)	797.57	--	802.30	802.27	802.16	802.01
	40	--	40	40	40	40
Price_reg (pk1 vs. opk23) ($/MWh)	--	804.19	802.30	802.27	802.16	802.01
	--	75	90	90	90	90
Price demand weighted_nreg ($/MWh)	74.90	--	81.94	80.56	76.89	75.32
Price demand weighted_reg ($/MWh)	--	107.26	114.74	114.74	114.74	114.73
Demand_nreg (pk1 vs. opk23) (MWh)	3036.49	--	2965.54	2965.95	2967.68	2969.86
	595.20	--	595.20	595.20	595.20	595.20
Demand_reg (pk1 vs. opk23) (MWh)	--	2937.16	2965.54	2965.95	2967.68	2969.86
	--	573.50	564.20	564.20	564.20	564.20

Output_nreg, Gas (pk1 vs. opk23) (MWh)	1890.49	--	1973.29	1944.61	1849.94	1826.93
	0	--	0	0	0	0
Output_nreg, Coal (pk1 vs. opk23) (MWh)	1146.00	--	992.25	1021.34	1117.74	1142.93
	595.20	--	595.20	595.20	595.20	595.20
Output_reg, Gas (pk1 vs. opk23) (MWh)	--	2329.12	1973.29	1944.61	1849.94	1826.93
	--	0	531.04	559.23	510.77	0
Output_reg, Coal (pk1 vs. opk23) (MWh)	--	608.04	992.25	1021.34	1117.74	1142.93
	--	573.50	33.16	4.97	53.43	564.20
Net permit trade_Gas (million tons/yr)	--	1.60	1.53	1.53	1.53	1.53
Net permit trade_Coal (million tons/yr)	--	-1.60	-1.53	-1.53	-1.53	-1.53
Permit price ($/ton)	--	35.00	50	50	50	50
Profit_nreg, Gas (million $/yr)	0	--	4.93	4.83	4.49	4.29
Profit_nreg,Coal (million $/yr)	0	--	62.0	50.7	19.5	4.88
Profit_reg, Gas (million $/yr)	--	14.9	16.4	16.4	16.6	16.5
Profit_reg, Coal (million $/yr)	--	242.00	283.00	281.00	275.00	274.00
Utility_nreg, Gas	--	--	--	0.005	0.022	0.042
Utility_nreg, Coal	--	--	--	0.049	0.093	0.048
Utility_reg, Gas	--	--	--	0.016	0.079	0.152
Utility_reg, Coal	--	--	--	0.245	0.747	0.935
Expected utility Gas	--	--	--	0.011	0.051	0.097
Expected utility Coal	--	--	--	0.147	0.420	0.491
Certainty Equivalent_Gas (million $/yr)	--	--	--	10.6	10.4	10.2
Certainty Equivalent_Coal (million $/yr)	--	--	--	159.00	109.00	67.6
Emissions Nreg Gas (million ton/yr)	0.53	--	0.79	0.726	0.56	0.53
Emissions Nreg Coal (million ton/yr)	8.63	--	8.03	8.17	8.54	8.62

Emissions Reg Gas (million ton/yr)	--	2.03	1.96	1.96	1.96	1.96
Emissions Reg Coal (million ton/yr)	--	5.30	5.37	5.37	5.37	5.37
Total Emissions_nreg (million ton/yr)	9.16	--	8.82	8.90	9.10	9.15
Total emissions_reg (million ton/yr)	--	7.33	7.33	7.33	7.33	7.33
Producer Surplus*[5]_nreg (million $/yr)	0	--	66.95	55.53	23.96	9.17
Producer Surplus_reg (million $/yr)	--	256.5	299.5	297.7	291.7	290.0
Consumer Surplus_nreg (billion $/yr)	4.48	--	4.41	4.43	4.46	4.47
Consumer Surplus_reg (billion $/yr)	--	4.18	4.11	4.11	4.11	4.11
Social Welfare**_nreg (billion $/yr)	4.48	--	4.48	4.48	4.48	4.48
Social Welfare**_reg (billion $/yr)	--	4.43	4.41	4.41	4.40	4.40
Baseline Emission_ Gas (million ton/yr)	0.53					
Baseline Emission _Coal (million ton/yr)	8.63					

Table 4: Example of solutions found with 80% Cap,
Grandfathered emission allowances[6], Capacity allocation rule
in a competitive market, multi periods model

Column 1	2	3	4	5	6	7
risk-aver coeff r:	Neutral	Neutral**	Neutral	1e-9	5e-9	1e-8
Free allowances *l*	Base	Reg 80%	80%	80%	80%	80%
Capacity_Gas (MW)	1890.49	2329.12	1973.29	1969.49	1941.19	1913.05
Capacity_Coal (MW)	1146.00	608.04	992.25	1001.56	1050.69	1098.82
Price_nreg, (pk1 vs. opk23) ($/MWh)	797.57	--	802.30	801.93	800.54	799.21
	40	--	40	40	40	40
Price_reg (pk1 vs.	--	804.19	802.30	801.93	800.54	799.21

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[5] * Producer Surplus in scenario i here is defined as the total profits of all operators in scenario i.
** Social welfare in scenario i is defined as the sum of producer surplus, consumer surplus, and government surplus.

[6] To consider scaling problem, I am using a scaling factor of 10,000,000 throughout the programming. In other words, the utility function I used in programming is $U = 100,000,000 - 100,000,000 * e^{-rx}$. But for simplicity, I just showed the solution values for the basic function $U = 1 - e^{-rx}$ here.

	--	75	90	90	90	90
Price demand weighted_nreg ($/MWh)	74.90	--	81.94	81.45	79.53	77.52
Price demand weighted_reg ($/MWh)	--	107.26	114.74	114.73	114.65	114.58
Demand_nreg (pk1 vs. opk23) (MWh)	3036.49	--	2965.54	2971.06	2991.88	3011.86
	595.20	--	595.20	595.20	595.20	595.20
Demand_reg (pk1 vs. opk23) (MWh)	--	2937.16	2965.54	2971.06	2991.88	3011.86
	--	573.50	564.20	564.20	564.20	564.20
Output_nreg, Gas (pk1 vs. opk23) (MWh)	1890.49	--	1973.29	1969.49	1941.19	1913.05
	0	--	0	0	0	0
Output_nreg, Coal (pk1 vs. opk23) (MWh)	1146.00	--	992.25	1001.56	1050.69	1098.82
	595.20	--	595.20	595.20	595.20	595.20
Output_reg, Gas (pk1 vs. opk23) (MWh)	--	2329.12	1973.29	1969.49	1941.19	1913.05
	--	0	0	129.83	145.63	0
Output_reg, Coal (pk1 vs. opk23) (MWh)	--	608.04	992.25	1001.56	1050.69	1098.82
	--	573.50	564.20	434.37	418.57	564.20
Net permit trade_Gas (million tons/yr)	--	-1.28	-1.35	-1.35	-1.35	-1.34
Net permit trade_Coal (million tons/yr)	--	1.28	1.35	1.35	1.35	1.34
Permit price ($/ton)	--	35.00	50	50	50	50
Profit_nreg, Gas (million $/yr)	0	--	4.93	4.54	3.05	1.66
Profit_nreg,Coal (million $/yr)	0	--	62.0	58.0	42.0	24.4
Profit_reg, Gas (million $/yr)	--	116.00	161.00	160.00	159.00	158.00
Profit_reg, Coal (million $/yr)	--	141.00	139.00	138.00	134.00	130.00
Utility_nreg, Gas	--	--	--	0.005	0.015	0.016
Utility_nreg, Coal	--	--	--	0.056	0.190	0.217
Utility_reg, Gas	--	--	--	0.148	0.548	0.793
Utility_reg, Coal	--	--	--	0.129	0.489	0.728

Expected utility Gas	--	--	--	0.076	0.282	0.405
Expected utility Coal	--	--	--	0.093	0.339	0.473
Certainty Equivalent_Gas (million $/yr)	--	--		79.4	66.2	51.9
Certainty Equivalent_Coal (million $/yr)	--	--		97.2	82.8	64.0
Emissions Nreg Gas (million ton/yr)	0.533	--	0.79	0.77	0.67	0.59
Emissions Nreg Coal (million ton/yr)	8.63	--	8.03	8.08	8.30	8.48
Emissions Reg Gas (million ton/yr)	--	2.03	1.96	1.96	1.96	1.97
Emissions Reg Coal (million ton/yr)	--	5.30	5.37	5.37	5.36	5.36
Total Emissions_nreg (million ton/yr)	9.16	--	8.82	8.85	8.97	9.07
Total emissions_reg (million ton/yr)	--	7.33	7.33	7.33	7.33	7.33
Producer Surplus*[7]_nreg (million $/yr)	0	--	66.95	62.50	45.10	26.10
Producer Surplus_reg (million $/yr)	--	256.5	299.50	298.35	293.15	288.07
Consumer Surplus_nreg (billion $/yr)	4.48	--	4.41	4.42	4.44	4.46
Consumer Surplus_reg (billion $/yr)	--	4.18	4.11	4.11	4.11	4.12
Social Welfare**_nreg (billion $/yr)	4.48	--	4.48	4.48	4.48	4.48
Social Welfare**_reg (billion $/yr)	--	4.43	4.41	4.41	4.41	4.40
Baseline Emission_ Gas (million ton/yr)	4.14					
Baseline Emission _Coal (million ton/yr)	5.02					

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[7] * Producer Surplus in scenario i here is defined as the total profits of all operators in scenario i.
** Social welfare in scenario i is defined as the sum of producer surplus, consumer surplus, and government surplus.