# Environmental Regulation in Transmission-Constrained Electricity Markets

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***Abstract*—We discuss potential competitive effects of regulating carbon emissions in a transmission constrained electricity market. We compare two regulatory instruments, renewable portfolio standards and taxing emmissions. We derive general conclusions about impacts on prices and output on a three node network. We find that renewable portfolio standards increase the market power of nonpolluting generators whereas the tax is market-power neutral. We verify our conclusions through simulations.**

## I. Introduction

The United States are moving fast towards regulating greenhouse gas (GHG) emissions. The electricity sector accounted for 40.6% of US energy consumption in 2007 and 70% of this energy was supplied by fossil fuel energy sources, namely natural gas, coal and oil. Therefore, the regulation of emissions is expected to have a major impact in the electric power industry.

One way of reducing GHG emissions is by promoting renewable generation. Due to the high long-run average costs of these resources, as well as the costs resulting from their variable and nondispatchable nature, regulatory intervention is required for integrating a significant capacity of these resources. For example, coal fired generation typically costs less than gas fired generation which costs less than renewable resources such as wind power and solar power. Therefore, introducing these resources at a large scale in power systems will inevitably impact the wholesale price of electricity, as well as electric power production costs, producer surplus and welfare [1]. It is also possible that emissions regulations will affect the strategic interaction between power generating firms, enhancing the market power of certain producers in the expense of others.

In this paper we compare two policies for regulating emissions by promoting renewable energy: renewable portfolio standards (RPS) and taxing emissions. RPSs require that a certain fraction of the energy which is generated or sold within a state be generated by renewable energy sources other than hydro power, such as wind, solar or geothermal power [1]. In some states, suppliers are allowed to purchase RECs (renewable energy credits) to fulfill their obligation. As of June 2007, RPS is implemented in more than half of the US states. For example the RPS targets in California require that 20 % of the energy sales originate from clean energy sources [2]. Unlike RPS which directly stipulates a requirement for electricity mix, taxes target emissions by making polluting technologies less competitive. Sweden, Denmark, Finland and Norway have $CO_2$ taxes with tax rates ranging widely [3]. For example, the Swedish tax rate is currently around 70$/ton while Norway rates differ for different sectors ranging from 12 to 47$/ton.

The analysis of the impacts induced by RPSs and tax is complicated by the presence of a transmission network. The effect of transmission constraints on strategic interactions in transmission networks have been studied extensively. In contrast, the research on the impact of emissions regulation in power markets mainly consists of empirical studies [4][5], with the exception of Chen and Hobbs [6]. In their work, Chen and Hobbs modeled how generators could manipulate the power market by using NOx emissions permits. In the spirit of [7] and [8] who focus on small scale networks in order to gain insight on firm interactions, in this paper we focus on a three node network and derive general conclusions about the impacts of emissions policies on nodal prices and generator output.

In future work we intend to expand our analysis to study the impacts of emissions trading. There is increasing concensus for the implementation of emissions trading in many US states. For example, California Assembly Bill 32 will mark the launch of an emissions trading program in California with the objective of reducing GHG emissions to 1990 levels by 2020. In terms of its impact on firm strategies, emissions trading is expected to be remarkably different from both RPS and taxing, and we intend to draw comparisons between these alternative policies in future work.

The rest of this paper is organized as follows. We describe our model in Section II. In Section III we present general results from our model and in Section IV we present specific examples which clarify the results of Section III. In Section V we present the conclusions of our analysis.

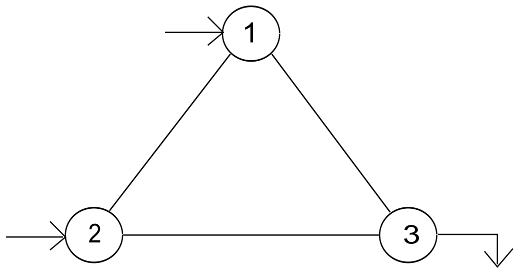


Fig. 1. A three node network of one load and two suppliers.

## II. Model

Our analysis focuses on a three-node power network, the simplest setting that still allows us to examine the interactions between transmission and environmental regulations by deriving closed form solutions for the output of the generators and for nodal prices. Due to the symmetry of the network which we are considering, without loss of generality we assume that a clean generator is located in node 1, a polluting generator in node 2 and load in node 3. Consistent with our presumption that nonpolluting generators are typically more expensive than conventional generators, we will assume that the generators in the three node network have constant marginal cost $c_i$, with $c_2 < c_1$. The inverse demand function at the node $i$ is assumed to be linear, given by the following expression: $P_i(x) = a_i - b_i x$.

Our formulation assumes the transmission network is operated by a welfare maximizing transmission system operator (TSO), similar to [9] The market is simulated as a Cournot game, whereby generators compete in the quantity of their output. Generators bid a quantity of power to be sold at the node in which they are located, and are rewarded the nodal price at their location. The TSO arbitrages any non-cost based difference in the locational price of electricity and clears the market with the objective of maximizing social welfare subject to the operational constraints of the network. We subsequently demonstrate that this formulation is equivalent to a Cournot competition in quantities with additional constraints imposed by both emissions reagulation as well as the capacity constraints of the network transmission lines. As in the case of classical Cournot competition, generators decide simultaneously about their output whereas the nodal price is determined by their joint decision.

We assume that generators do not anticipate the effect of their decisions on the locational pricing of electricity by the TSO. In other words, generators behave as price takers in transmission services [10]. To exemplify this assumption, a generator which is being charged for congesting the network cannot anticipate that by slightly reducing output it can decongest the grid and avoid paying a price for scarce transmission.

### A. RPS Policy

Increase the penetration of renewable energy sources in the supply mix is expected to increase the overall cost of supplying power. These additional costs are born by generators and propagated to some extent, through prices, to consumers. In order to capture this effect in our model, we have assumed that the RPS goal is imposed as an operational constraint in the TSO dispatch model. Hence, the RPS policy is included in the TSO optimization problem explicitly, and emissions are priced in a similar fashion to transmission services. In the TSO problem, the RPS constraint requires that the proportion of energy that is supplied by firms which use polluting fuels cannot exceed a specified fraction $f$ of the total energy supply. This is equivalent to setting an RPS requirement of $1-f$, i.e. requiring that the fraction of power supplied by nonpolluting sources exceeds $1-f$. The TSO optimization problem is the following:

$$TSO : \max_{r_i} W = \sum_{i \in N} \left( \int_0^{q_i + r_i} P_i(x) dx - c_i q \right)$$

$$\begin{aligned}
& s.t. \\
& \sum_{i \in N} r_i = 0 && (p) \\
& \sum_{i \in N} D_{l,i} r_i \leq K_l && (\lambda_l^+) \quad l \in L \\
& -\sum_{i \in N} D_{l,i} r_i \leq K_l && (\lambda_l^-) \quad l \in L \\
& -\sum_{i \in N} (d_i - f) r_i \leq 0 && (\mu).
\end{aligned}$$

We denote $N$ the set of nodes and $L$ the set of arcs. The goal of the TSO is to regulate flows in the network in order to maximize social welfare $W$. The TSO decision variables are $r_i$, the quantities of power imported from node $i$ to the hub node (negative for export). The hub node is chosen arbitrarily as the load node, namely node 3. $P_i$ is the nodal price. The first constraint in the problem is a mass-balance constraint which requires that the TSO is neither a net producer nor net consumer of energy. The second and third constraints ensure that the network transmission constraints are satisfied. In these constraints, $K_l$ denotes the capacity limit of line $l$ and $D_{l,i}$ denotes the power transfer distribution factor (PTDF) between line $l$ and node $i$, the exact meaning of which is explained in the next paragraph. The last constraint is the RPS constraint imposed on the operation of the network, whereby the output of polluting generators cannot exceed a fraction $f$ of total output. In this constraint, $d_i$ is an indicator parameter equal to 1 if the firm located at node $i$ operates a polluting generator, and 0 otherwise. The symbols in parentheses denote the Lagrange multipliers of the TSO problem which will be used subsequently for pricing electricity. Capacity constraints on the output of generators can be included in the problem, but have been omitted since they do not add insight to the current analysis.

We use a DC-approximation of Kirchhoff's Laws to model power flow in the network by PTDFs. The entry $D_{l,i}$ in the PTDF matrix specifies the proportion of power which flows through line $l$ when a unit of power is being transmitted from the hub to node $i$. For example, $D_{1-2,2} = 0.8$ implies that if

1 MW of power were to flow from node 2 to the hub (node 3), 0.8 MW would flow through line 1-2.

Prices act as a mechanism by which the TSO can signal or direct generators to either increase or reduce their output in order to satisfy the operational constraints of the system. This is clarified by the following KKT conditions of the TSO, where the symbol $\perp$ indicates complementarity between variables and their corresponding constraints:

$$\begin{array}{ll}
P_i(q_i+r_i)-p-\phi_i-\psi_i=0 & i\in N\\
\sum_{i\in N} r_i=0 & \\
\phi_i=\sum_{l\in L}(\lambda_l^+-\lambda_l^-)D_{l,i} & i\in N\\
\psi_i=\mu(f-d_i) & i\in N\\
0\le\lambda_l^-\perp\sum_{i\in N}D_{l,i}r_i+K_l\le 0 & l\in L\\
0\le\lambda_l^+\perp K_l-\sum_{i\in N}D_{l,i}r_i & l\in L\\
0\le\mu\perp\sum_{i\in N}(d_i-f)q_i\le 0. &
\end{array}$$

From the preceding first-order conditions we obtain the congestion and pollution rents which are imposed in the various nodes of the netwrok. The congestion rents $\phi_i = \sum_{l\in L}(\lambda_l^+-\lambda_l^-)D_{l,i}$ are equal to the marginal value of the congested transmission lines weighted by the extent to which a generator utilizes the congested lines. These rents will be negative (i.e. costs) whenever a generator contributes to the congestion of a line, and positive (i.e., revenues) otherwise. Similarly, pollution rents are given by the expression $\psi_i = \mu(f-d_i)$. These rents reward nonpolluting producers and penalize polluting generators whenever the RPS constraint is binding.

According to our model assumptions, firms correctly anticipate the impact of their actions on price at the load node but as we have mentioned previously firms act as price takers in transmission services and pollution charges. Therefore, whereas the price $p$ is endogenous to the firm oprimization problem, both congestion and pollution rents $\phi$ and $\psi$ are exogenous to the problem. The firm optimization problem is therefore given by the following:

$$\begin{array}{l}
\mathscr{F}_i:\max_{q_i}(p(q_i)+\phi_i+\psi_i)q_i-c_iq_i\\
s.t.\\
0\le q_i.
\end{array}$$

Given our formulation, the price at the location of a generator can be obtained by adding pollution and congestion rents to the hub price. This allows us to treat the competition between generators as a constrained Cournot game where firms need to additionally satisfy transmission and emissions constraints.

### B. Taxing

The alternative policy which we consider, taxing, is readily incorporated in the model. We assume that polluting generators are levied with an amount $t$ per MWh of output, which is not imposed to renewable generators. Therefore, the TSO does not include emissions regulation as an operational constraint in its optimization problem:

$$TSO:\max_{r_i} W=\sum_{i\in N}(\int_0^{q_i+r_i}P_i(x)dx-c_iq)$$

$$\begin{array}{lll}
s.t. & & \\
\sum_{i\in N} r_i=0 & (p) & \\
\sum_{l\in L}D_{l,i}r_i\le K_l & (\lambda_l^+) & l\in L\\
-\sum_{l\in L}D_{l,i}r_i\le K_l & (\lambda_l^-) & l\in L.
\end{array}$$

As in the case of RPS, we derive the KKT conditions of the TSO problem which will be necessary for obtaining closed form solutions subsequently.

$$\begin{array}{ll}
P_i(q_i+r_i)-p-\phi_i=0 & i\in N\\
\sum_{i\in N} r_i=0 & \\
\phi_i=\sum_{l\in L}(\lambda_l^+-\lambda_l^-)D_{l,i} & i\in N\\
0\le\lambda_l^-\perp\sum_{i\in N}D_{l,i}r_i+K_l\le 0 & l\in L\\
0\le\lambda_l^+\perp K_l-\sum_{i\in N}D_{l,i}r_i & l\in L.
\end{array}$$

The tax enters the model formulation only in the optimization problems of the firms:

$$\begin{array}{l}
\mathscr{F}_i:\max_{q_i}(p(q_i)+\phi_i)q_i-(c_i+d_it)q_i\\
s.t.\\
0\le q_i.
\end{array}$$

## III. Results

In this section we present results of the three-node network problem which we introducd previously. We begin from the simplest possible scenario of a network in which the competitive outcome does not violate transmission constraints or RPS requirement. We derive the classical Cournot competition result, as well as its counterpart of taxation. We then move to a second scenario in which the unconstrained equilibrium violates the RPS policy. We present the equilibrium resulting from an RPS policy, as well as from a taxing policy which reproduces the RPS goal. Finally, we consider a third scenario where the unconstrained equilibrium violates transmission constraints, and again we obtain the equilibrium resulting from an RPS and tax policy.

### A. Unconstrained Equilibrium

If neither transmission nor pollution constraints are violated in equilibrium, then we obtain the familiar results of classic Cournot competition. This equilibrium serves as a benchmark upon which we compare more complicated outcomes. We will use superscripts to identify the outcomes in the various cases, and here c denotes the results of Cournot competition.

$$\begin{array}{cc} q_1^c = \frac{a-2c_1+c_2}{3b}, & q_2^c = \frac{a-2c_2+c_1}{3b}, \\ q^c = \frac{a-c_1-c_2}{3b}, & p^c = \frac{2a+c_1+c_2}{3}. \end{array} \tag{1}$$

where $q = q_1 + q_2$ and $p = p_1 = p_2 = p_3$ is the common price at all nodes. Taxing generator 2 is equivalent to increasing its marginal cost from $c_2$ to $c_2 + t$, and we can use the results of the previous paragraph to obtain the Cournot equilibrium under taxation, and to assess its impact on price and output.

$$\begin{array}{cc} q_1^{\text{tax}} = q_1^c + \frac{t}{3b} > q_1^c, & q_2^{\text{tax}} = q_2^c - \frac{2t}{3b} < q_2^c, \\ q^{\text{tax}} = q^c - \frac{t}{3b}, & p^{\text{tax}} = p^c + \frac{t}{3} > p^c. \end{array} \tag{2}$$

In classic Cournot competition, the output of a firm is decreasing in its marginal cost, and increasing in its competitor's marginal cost. Therefore, by increasing the marginal cost of generator 2, output will shift from generator 2 to generator 1, which is exactly the desired result of the regulatory mechanism. However, because the overall output is proportional to the sum of the firms' marginal costs, overall output will decrease and prices will increase at the load. Ultimately, the extent to which output shifts from one competitor to the other depends on demand elasticity. In the extreme case where demand is completely inelastic, the increase in the output of generator 1 will fully substitute the decrease in the output of generator 2. Nevertheless, overall generation under taxation cannot increase.

### B. Pollution Constrained Equilibrium

*1) RPS:* If $\frac{q_2^c}{q_1^c+q_2^c} = \frac{a-2c_2+c_1}{2a-c_1-c_2} > f$ the unconstrained duopoly outcome violates the pollution constraint. The Lagrange multiplier $\mu$ becomes active, and the resulting problem can be treated as a Cournot duopoly with modified marginal costs $c_1 - \psi_1 = c_1 - f\mu$ and $c_2 - \psi_2 = c_2 + (1-f)\mu$ where the generators obey the additional constraint $\frac{q_2}{q_1+q_2} = f$.

$$\begin{array}{cc} q_1^p = q_1^c + \frac{2\psi_1-\psi_2}{3b} > q_1^c, & q_2^p = q_2^c + \frac{2\psi_2-\psi_1}{3b} < q_2^c, \\ q^p = q^c + \frac{\psi_1+\psi_2}{3b}, & p_1^p = p^c + \frac{2\psi_1-\psi_2}{3} > p_c, \\ p_2^p = p^c + \frac{2\psi_2-\psi_1}{3} < p^c, & p_3^p = p^c - \frac{\psi_1+\psi_2}{3}. \end{array} \tag{3}$$

where the superscript p refers to the equilibrium when pollution constraint is binding. It follows from the closed form expression of $\psi_1$ and $\psi_2$ (which we do not present here) that the nodal price and the output at node 1 will increase and the opposite will be true for node 2. If $f < 0.5$ the pollution constraint will certainly be binding because in the unconstrained equilibirum $q_1^c < q_2^c$. From the closed form expressions of $\psi_i$ we can also conclude that for $f < 0.5$ the total output will be less than the unconstrained output because the reduction in polluting generation is not fully compensated by an increase in clean generation. The opposite will be true when $f > 0.5$.

Overall, it is clear that RPS enhances the profitability of generator 1 at the expense of generator 2. The impact on load prices depends on the specific value of $f$, and for stringent regulations ($f < 0.5$) price at the load increases, whereas for less stringent regulations price at the load decreases due to a dampening in the market power of generator 2.

*2) Taxing:* In order to compare RPS with taxing on an objective basis, we consider the particular case where the tax $t$ results in the RPS requirement $\frac{q_2}{q_1+q_2} = f$. The tax $t_f$ for which this equilibrium holds is given by the following equation:

$$t_f = \frac{3b(q_2^c - fq^c)}{2-f}, \tag{4}$$

where the relevant quantities are indexed by superscript $f$. By substituting the closed form of $\mu = \frac{q_2^c - fq^c}{2(1-f+f^2)}$ in equations 3 and the closed form of $t_f$ into equations 2 we obtain the following inequalities which can be used to compare the two policies:

$$\begin{array}{ccc} q_1^f < q_1^p & q_2^f < q_2^p, & q^f < q^p \\ p^f > p_2^p, & p^f > p_3^p. & \end{array} \tag{5}$$

We can see that both generators will reduce their output. The reason is that taxing, unlike RPS, does not offer sufficient incentives to generator 1 for increasing its output. As a result, electricity price at demand node increases, which is an undesirable side effect of this regulation.

### C. Transmission Constrained Equilibrium

In this section it is assumed that the unconstrained equilibrium violates one or more transmission constraints. In the spirit of traditional literature on market power in electricity networks, this section focuses on investigating how constraints influence the market power of generators.

*1) RPS:* We will consider a symmetric network, in which all transmission lines have the same impedance and capacity. Because power flow along a route is inversely proportional to the impedance of the route, one third of the power produced by each generator follows the short path to the load and the remaining two thirds follow the long path. Generator 2 produces at lower marginal cost, hence its output would be greater in an unconstrained network. Therefore, the first line to become congested will be line $2-3$. This problem is equivalent to a Cournot duopoly where the marginal cost of generator $i$ is $c_i - \phi_i$ under the additional constraint $\frac{1}{3}q_1 + \frac{2}{3}q_2 = K$, where $\phi_i = D_{2-3,i}\lambda_{2-3} < 0$ is the transmission charge at node $i$. Solving the corresponding system of equations we obtain the following closed form expressions:

$$\begin{array}{cc} q_1^t = q_1^c + \frac{2\phi_1-\phi_2}{3b} = q_1^c, & q_2^t = q_2^c + \frac{2\phi_2-\phi_1}{3b} < q_2^c, \\ q^t = q^c + \frac{\phi_1+\phi_2}{3b} < q^c, & p_1^t = p^c + \frac{2\phi_1-\phi_2}{3} = p^c, \\ p_2^t = p^c + \frac{2\phi_2-\phi_1}{3} < p^c, & p_3^t = p^c - \frac{\phi_1+\phi_2}{3} > p^c. \end{array} \tag{6}$$

The congestion charges for generator 2 are twice as large as for generator 1, $\phi_2 = 2\phi_1$, because it contributes twice the flow in the congested line, compared to its competitor. In summary, generator 2 produces a smaller output at a lower price compared to the unconstrained duopoly, whereas generator 1 produces the same output at a higher price. The overall output is reduced, therefore the price at the load increases.

It is also possible that the equilibrium is simultaneously binding in both the transmission and the pollution constraint (if $\frac{q_2^t}{q_1^t+q_2^t} > f$). The outcome can then be obtained by modifying the margnal costs of the generators by $c_i - \phi_i - \psi_i$ and adding the additional contraints that $\frac{q_2}{q_1+q_2} = f$ and $\sum_i D_{l,i} q_i = K_l$ where $l$ is the index of the congested line. In contrast to previous cases, the closed form solutions do not allow us to draw any general conclusion about how this outcome compares to the outcome of an unconstrained Cournot duopoly, therefore at this point we only present the resulting closed form solutions and defer to the examples for providing specific interpretations about the influence of simultaneous congestion and pollution constraints on firm strategies.

$$\begin{array}{rlrl} q_1^{p,t} &= q_1^c + \frac{2(\psi_1+\phi_1)-\psi_2-\phi_2}{3b}, & q_2^{p,t} &= q_2^c + \frac{2(\psi_2+\phi_2)-\psi_1-\phi_1}{3b}, \\ q^{p,t} &= q^c + \frac{\psi_1+\phi_1+\psi_2+\phi_2}{3b}, & p_1^{p,t} &= p_1^c + \frac{2(\psi_1+\phi_1-\psi_2)-\phi_2}{3}, \\ p_2^{p,t} &= p_2^c + \frac{2(\psi_2+\phi_2)-\psi_1-\phi_1}{3}, & p^{p,t} &= p^c + \frac{\psi_1+\phi_1+\psi_2+\phi_2}{3}. \end{array} \quad (7)$$

*2) Taxing:* When taxed firms operate under binding transmission constraints, we obtain the closed form solutions by modifying the marginal cost of generator 2 to $c_2 - t$ and adding the constraint that $\sum_l D_{l,i} q_i = K$ where $l$ is the index of the congested line. We obtain the following closed form solutions:

$$\begin{array}{rlrl} q_1^{\text{tax,t}} &= q_1^c + \frac{2\phi_1-(\phi_2-t)}{3b}, & q_2^{\text{tax,t}} &= q_2^c + \frac{2(\phi_2-t)-\phi_1}{3b}, \\ q^{\text{tax,t}} &= q^c + \frac{\phi_1+\phi_2-t}{3b}, & p_1^{\text{tax,t}} &= p^c + \frac{2\phi_1-(\phi_2-t)}{3}, \\ p_2^{\text{tax,t}} &= p^c + \frac{2(\phi_2-t)-\phi_1}{3}, & p_3^{\text{tax,t}} &= p^c + \frac{\phi_1+\phi_2-t}{3}. \end{array} \quad (8)$$

As in section III-B, it is useful to determine a tax $t_{f,t}$ which achieves the RPS policy, i.e. results in $\frac{q_2}{q_1+q_2} = f$. The derivation of $t_{f,t}$ is straightforward, but we omit it here since it does not contribue to the analysis. However, it is worth noting that $t_{f,t}$ is a function of demand parameters $a$, $b$, firm cost parameters $c_i$ as well as the PTDFs $D_{l,i}$ on the congested line. When taxing by $t_{f,t}$, the equilibrium which is obtained is identical to the equilibrium of equations 7, with the exception of the price at node 2:

$$\begin{array}{lll} q_1^{f,t} = q_1^{p,t}, & q_2^{f,t} = q_2^{p,t}, & q^{f,t} = q^{p,t}, \\ p_1^{f,t} = p_1^{p,t}, & p_2^{f,t} = p_2^{p,t} + t_{f,t}, & p_3^{f,t} = p_3^{p,t}. \end{array} \quad (9)$$

As we mentioned previously, $t_{f,t}$ depends on firm cost parameters, which may be unknown to a central regulator. Even if these parameters were common knowledge, since $t_{f,t}$ is a function of distribution factors on the congested line, in order to enforce a static $t_{f,t}$ which achieves the second best outcome subject to the RPS constraint the regulator would need to predict which lines will be congested and these congestion patterns would need to remain unchanged over time $t_{f,t}$. Finally, $t_{f,t}$ depends on demand parameters which vary throughout time, again contradicting the requirement that $t_{f,t}$ be a static measure. Therefore, though more succesful in evenly redistributing market power, taxing would not yield second best outcomes because it cannot dynamically adjust to the conditions of the market.

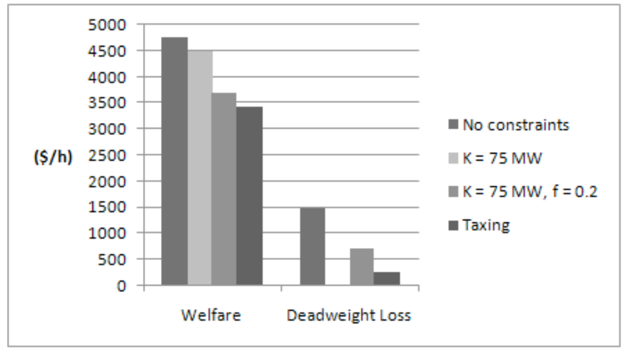


Fig. 2. Welfare and deadweight loss in the oligopolistic market.

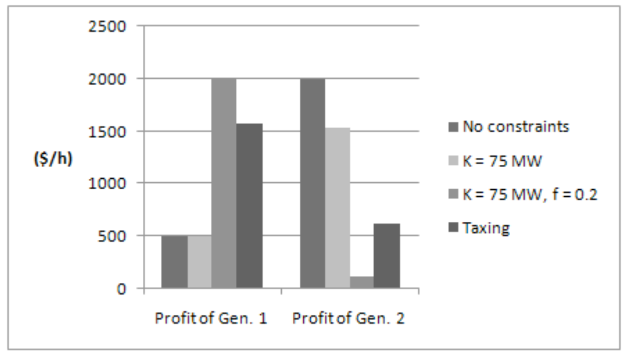


Fig. 3. Profits in the oligopolistic market.

## IV. Examples

In this section we present three examples. The first example is the solution to a symmetric three node network, which confirms various conclusions which we drew in the previous section. In the second example we examine the sensitivity of optimal firm strategies on the regulatory parameters $t$ and $f$ which were introduced earlier. In the third example we demonstrate that emisisons regulations might be vulnerable to gaming by providing an example of a nonpolluting generator which manipulates regulations in order to limit the participation of its polluting competitor in the local power market.

### A. Full Example

We solve an example with a symmetric network. The PTDF matrix of the network is given in table I. The inverse demand function is $P(q) = 70 - 0.2q$. The marginal costs are $c_1 = 30$\$/MWh, $c_2 = 20$\$/MWh.

The results of the duopoly equilibria are shown in Figs. 2, 3 and Table II, where the first case refers to an unconstrained

TABLE I
Power transfer distribution factors for the symmetric three node network of the first example

| | Node 1 | Node 2 | Node 3 |
|---|---|---|---|
| Line 1-2 | $\frac{1}{3}$ | $-\frac{1}{3}$ | 0 |
| Line 2-3 | $\frac{1}{3}$ | $\frac{2}{3}$ | 0 |
| Line 3-1 | $-\frac{2}{3}$ | $-\frac{1}{3}$ | 0 |

system; the second case refers to a system with a thermal limit of $K = 75$MW for each line; the third case refers to a system with a pollution constraint of $f = 0.2$ and transmission constraints of $K = 75$MW; the last case refers to a system where taxing is enforced on generator 2. Table II indicates that under transmission constrained operation (Case 2), generator 2 is forced to reduce its output in order to decongest transmission line $2-3$, and prices at the load increase. Generator 1 is not affected by the transmission constraints and maintains the same output as in the unconstrained equilibrium. Also shown in Table II,the price at node 2 drops in Case 3, and the price at node 1 increases where the output shifts from generator 2 to generator 1. Since the RPS requirement is less than 0.5, the price at the load is higher because the overall output decreases. From section III-B, the tax for achieving the goal $f = 0.2$ is $t_f = 23.3$ \$/MWh. This leads us to consider Case 4, where we implement a tax to reproduce the RPS goal of Case 3. Table II suggests that the output of each generator decreases and the price at the load increases at a higher level than the resulting load price from RPS. From Fig. 3 it is clear that this policy is more balanced in terms of redistributing profits compared to RPS, nevertheless deadweight loss – mainly consumer surplus – is greater. This can be attributed to the significant reduction of total output.

The examples indicate that RPS results in an undermining of the market power of generator 2, though the overall output in the market remains larger than in the case of taxing because RPS is effective in redistributing incentives to generator 1 rather than discouraging production altogether. Since the RPS target in this exampe is quite aggressive, the impact of transmission constraints has no noticeable impact on firm strategies, and it is instead the pollution regulations which drive the results.

### *B. The effect of RPS ($f$) and taxing ($t$) on firm strategies*

In this section we consider the effect of emissions regulations on firm strategies. We vary the parameters that characterize the two policies, $f$ for RPS and $t$ for taxing, in order to know how might firms' optimal output respond to the changes. The resulting graphs are shown in Fig. 4. We consider both the case where the network has unlimited transmission capacity, as well as the case where all lines have a 75MW thermal limit.

In the top of Fig. 4 we graph equilibrium strategies parametrized on $f$. For $f < 0.5$ the output of generator 1 is obviously greater and from the overlap of the two lines, we conclude that none of the transmission constraints are binding. At $f = 0.5$ lines $1-3$, $2-3$ become congested and firm

TABLE II
PRICES AND PRODUCTION LEVELS FOR DUOPOLY.

| | $p_1$ | $p_2$ | $p_3$ | $q_1$ | $q_2$ | q |
|---|---|---|---|---|---|---|
| No constraints | 40 | 40 | 40 | 50 | 100 | 150 |
| $K = 75$ MW | 40 | 37.5 | 42.5 | 50 | 87.5 | 137.5 |
| $f = 0.2$, $K = 75$ MW | 50 | 25 | 45 | 100 | 25 | 125 |
| Taxing | 47.8 | 47.8 | 47.8 | 89 | 22 | 111 |

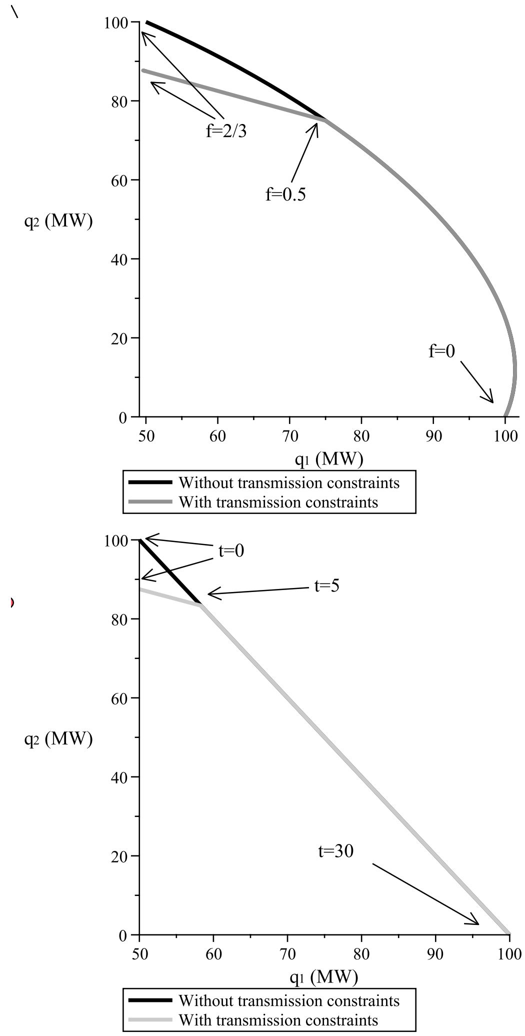


Fig. 4. The equilibria parametric on $f$ and $t$.

outputs become equal at 75MW. As $f$ increases, the output of generator 2 dominates, and line $2-3$ is now the only congested line. At $f = 0.64$ the pollution constraint is no longer binding, with line $2-3$ remaining congested.

In the bottom of Fig. 4 we consider the response of equilibrium strategies to $t$. For $t < 5$\$/MWh generator 2 produces most of the output and line $2-3$ is congested. When the tax exceeds 5\$/MWh, line $2-3$ is no longer congested and the output of generator 2 continues to decrease up to $t = 15$\$/MWh, at which point the output of both generators becomes equal. For $t > 15$\$/MWh generator 1 produces most of the output without congesting the transmission lines and total output decreases as tax increases. For $t = 30$\$/MWh generator 2 will stop producing power. Note that this tax is greater than the marginal cost of generator 2, and the reason generator 2 can continue to generate output at taxes higher than its marginal cost is the duopoly markup on the price.

Fig. 4 reaffirms our conclusion that generator 1 benefits greatly from RPS pricing whereas taxing results in a comparatively balanced redistribution of generator outputs. In addition,

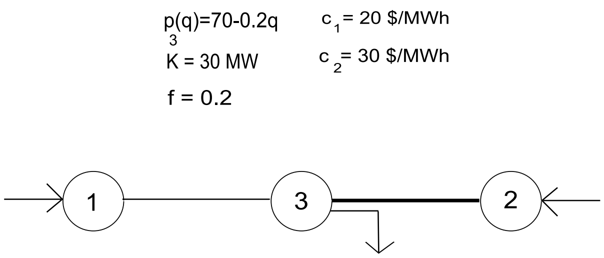


Fig. 5. An example where RPS pricing results in underutilization of transmission capacity.

the graphs confirm the fact that generator 1 is incented to sustain a relatively higher output compared to the taxing case. In fact, total output under taxing is significantly smaller for all but a small range of parameter values in the two graphs. Finally, the effect of transmission constraints becomes noticeable for relatively large values of $f$ and $t$ and does not seem to benefit any one generator.

### *C. An Example of Gaming RPS*

Investing in transmission is desirable from an efficiency standpoint because, with few exceptions, it leads to increased competition across the network. In the example that follows, we show how it is possible for the nonpolluting generator to offset the benefits of large line capacities by manipulating RPS in order to constrain the participation of its competitor in the local market.

In the network of Fig. 5 generator 1 has unconstrained access to the load, whereas generator 2 is connected to the load through a capacity constrained line, and there is no link between nodes 1 and 2. For sufficiently low capacity of the line $2-3$, generator 1 will be able to exercise market power at a significant extent. Since the participation of generator 2 is limited by the capacity of line $2-3$, there is a large portion of the market which is anyways unreachable by generator 2 and on which generator 1 can exercise monopolistic market power by restricting output in order to boost prices. This effect is mitigated as the capacity of line $2-3$ is increased and generator 2 is allowed to penetrate in the market. However, beyond a certain value of the line capacity generator 1 will cap its own output in order to halt the penetration of generator 2 in the market via the RPS constraint. This will happen at the point where the incremental benefits for generator 1 of sustaining a high price by withholding its own output as well as that of its competitor (throught the RPS constraint) exceed the incremental benefits of achieving higher revenues by supplying a higher output. The threshold of line capacity at which generator 1 exercises this form of market power is the value of $K$ beyond which the capacity of transmission line $2-3$ exceeds the RPS-constrained output of generator 2:

$$K = \frac{f(a-(1-f)c_1 - fc_2)}{2b(1-f+f^2)}.$$

These ideas are clarified by the graphs in Figs. 6, 7. In Fig. 6 we see the output of both generators as it varies with respect to $K$, for both the case where RPS constraints are not enforced and the case where they are enforced. For sufficiently low values of $K$, specifically for $K \leq 22.2$ MW, generator 1 relies on the transmission line to keep its competitor away form the market. In this region, as $K$ increases the output of generator 1 increases in response to the increasing penetration of generator 2 in the market. At $K = 22.2$MW the RPS constraint becomes active and generator 1 continues increasing its output. Generator 2 also increases its output in this intermediate range of values of $K$, where both the RPS as well as the transmission constraint are active. However, at the threshold value of $K = 25$MW generator 1 finally witholds output, in order to constrain the penetration of its competitor and keep prices high at the load. For any value of $K$ greater than this threshold value the output of both generators remains fixed, therefore line capacity greater than 25MW does not contribute to enhancing competition in this market.

In Fig. 7 we have plotted the evolution of $\frac{q_2}{q_1+q_2}$ and $p_3$ with respect to $K$. We observe that, indeed, beyond $K = 25$ MW the RPS constraint is tight with $\frac{q_2}{q_1+q_2} = 0.2$. It is worth noting that prices at the load are not necessarily greater in the case when RPS constraints are enforced, since as we have mentioned previously, RPS is effective in depressing the market powe rof generator 2 and incenting generator 1 to sustain a high output. However, for large values of $K$ generator 1 is abusing the RPS constraint and achieving a price at the load whoich is higher than it would have been otherwise.

From this example, it becomes clear that RPS will require tight regulatory monitoring, in order to ensure that nonpolluting generators which have become empowered from the new market rules do not abuse these rules. We can also conclude that these regulations will achieve their desired results without leading to uninteded consequences if it is ensured that there exists a sufficient population of nonpolluting generators which compete with eachother, not only with polluting competitors. In particular, California resembles the configuration of Fig. 5 as it is a net importer of polluting generation, with significant capacity of in-state renewable energy. In addition, California is pursuing aggressive emissions regulations and renewable energy standards, therefore close monitoring of the market conduct of clean suppliers will be essential.

## V. CONCLUSIONS

In this paper we explore the strategic interactions between generators in a transmission constrained netwrok, under the additional constraint of pollution regulation. We focus on two regulatory mechanisms, renewable portfolio standards and taxing. We compare the outcome of a pollution constrained game with an unconstrained Cournot duopoly and demonstrate how the nonpolluting generator increases its competitive advantage under both regulatory mechanisms. We find that taxing is neutral in terms of redistributing market power, however we observe that in order to achieve an RPS goal, efficient taxing relies on temporally varying network parameters, as well as information which the regulator does not have access to. Fianlly, we identify a potential gaming opportunity for a

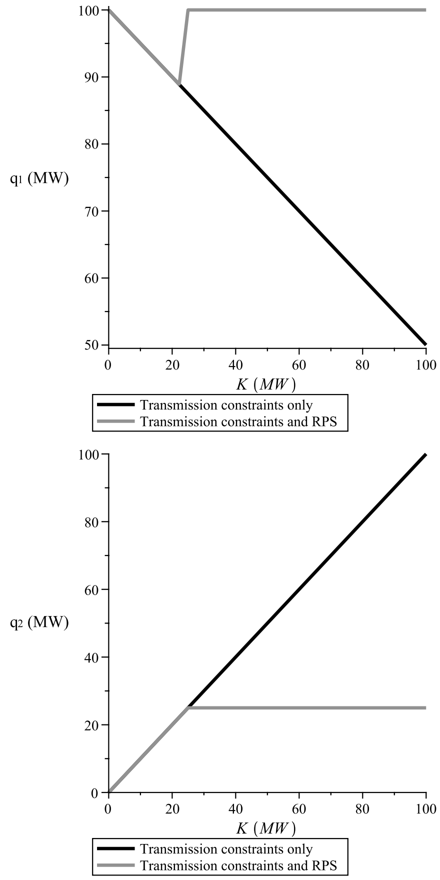


Fig. 6. Generation as a function of $K$ for the third example.

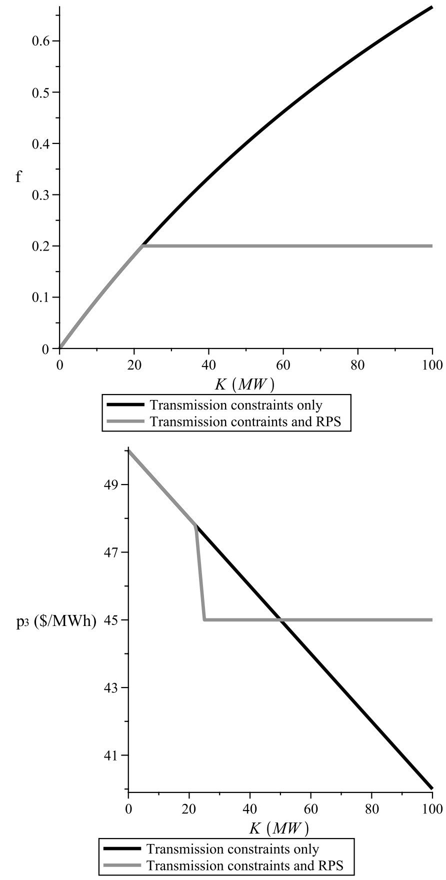


Fig. 7. Price at the load and $\frac{q_2}{q_1+q_2}$ as a function of $K$ for the third example.

nonpolluting generator which supplies power to a load pocket with limited access to alternative generators. The example raises concerns about inefficient transmission line utilization and suggests that efficient pollution regulation will require tight regulatory monitoring, especially in states like California which is independently investing in in-house clean generation and relies on importing residual energy demand from neighboring fossil fuel generators.

## ACKNOWLEDGMENT


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## REFERENCES


[1] K. Palmer and D. Burtraw, "Cost-effectiveness of renewable electricity policies," *Energy Economics*, vol. 27, pp. 873–894, 2005.

[2] C. Loutan and D. Hawkins, "Integration of renewable resources," CAISO, Tech. Rep., 2007.

[3] C. Fischer and R. Newell, "Environmental and technology policies for climate mitigation," *Journal of Environmental Economics and Management*, vol. 55, no. 142–162, 2008.

[4] P. C. et. al, "The primes energy system model: Reference manual," National Technical University of Athens, Greece, Greece, Tech. Rep., 2000.

[5] J. Kolsatd and F. Wolak, "Using environmental emissions permit prices to raise electricity prices: Evidence from the california electricity market," University of California Energy Institute, CSEM–113, Berkeley, CA, Tech. Rep., 2003.

[6] Y. Chen and B. F. Hobbs, "An oligopolistic power market model an oligopolistic power market model with tradable nox permits," *IEEE Transactions on Power System*, vol. 20, no. 119–129, 2006.

[7] J. Cardell, C. Hitt, and W. Hogan, "Market power and strategic interaction in electricity networks," *Resources and Energy Economics*, vol. 19, no. 1–2, pp. 109–137, 1997.

[8] S. Borenstein, J. Bushnell, and S. Stoft, "The competitive effects of transmission capacity in a deregulated electricity industry," *The RAND Journal of Economics*, vol. 31, no. 2, pp. 294–325, 2000.

[9] R. Kamat and S. S. Oren, "Two-settlement systems for electricity markets under network uncertainty and market power," *Journal of Regulatory Economics*, vol. 25, no. 1, 2004.

[10] B. F. Hobbs, "Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets," *IEEE Transactions on Power System*, vol. 16, no. 2, pp. 194–202, 2001.