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Who Should Own a Renewable Technology? Ownership Theory and an Application

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Abstract

We investigate the market implications of ownership of a new low-cost production technology. We relate our theoretical findings to measuring the impact of renewable energy penetration into electricity markets and examine how the ownership of renewable capacity changes market outcomes (prices, outputs, emissions). As the current public policies influence the renewable energy ownership, this research provides useful insights for policy makers. We show that ownership of renewable capacity will matter when there is market power in energy market. We apply our findings to the Ontario wholesale electricity market to analyze the impact of different ownership structures for wind capacity expansions. We show that consumers enjoy better air quality under the largest firm's ownership, but at the expense of higher prices. We find that market structure and the shape of generation cost functions are the key drivers explaining the impact of renewable ownership on market outcomes.

Keywords: Market structure; technology ownership; renewable energy; greenhouse gas emissions.

JEL codes: D4; L1; Q5; Q4; Q2.

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1 Introduction

Investments in renewable energy have seen record levels and been expanding at a fast pace almost everywhere in the world. For example, in 2013 about $113.7 billion was invested for solar power, and $80.1 billion invested for wind generation (following the same level in 2012) throughout the world (see Renewables 2014 Report). In Ontario, Canada, which is a subject of the current paper, due to the Ontario's Green Energy Act the government has signed a contract with a consortium (Samsung C&T Corporation and the Korea Electric Power Corporation) in 2010 to construct new green energy facilities which will triple Ontario's renewable wind and solar energy generation over time. In 2010 Ontario had about 1,200 MW installed wind generation capacity and 40 MW of solar capacity. Due to the (price and investment) incentives given to the green energy developers and producers, many firms submit their proposed projects to get approval from the energy regulators and/or government. However, the total proposed capacity investments typically exceed the target expansion plans. Therefore, the government/regulator needs to decide which firms get the right to operate wind/solar farms. In essence we address the following question: if w MW capacity would be added into the system, would it matter whether firm A or firm B owned this new capacity? Specifically, does the ownership of green technologies impact market outcomes and air quality, in particular wholesale and retail prices, outputs, producer and consumer surplus, NOx, SO2, and CO2 emissions?

Many countries have implemented "Green Energy Acts" or "Renewable Energy Laws" to promote development of renewable energy supply and increase power production mainly from wind and solar energies so as to diversify the generation portfolio, meet environmental targets, and improve air quality. For instance, Germany expects to meet 20% of its electricity demand using renewable energy by 2020 and 65% of its electricity needs by 2050. The USA targets 25% of demand to be met by green technologies by 2025. The global electricity supply by wind generation in 2020 is expected to be 8-12% of the total supply.[1]

Several studies have examined the impact of wind generation on several issues such as

[1] See http://www.gwec.net/global-figures/wind-in-numbers/

emissions, market prices, outputs of conventional generators, hydropower storage, power trade, and investment incentives; Denny and O'Malley (2006), Benitez et al. (2008), Callaway and Fowlie (2009), Traber and Kemfert (2011), Cullen (2013), Aydemir and Genc (2014), Novan (forthcoming). Most of these papers assume perfect competition and show that under certain market conditions wind generation yields emissions reductions.[2] In contrast to these papers, we focus on wind generation ownership. To our knowledge this is the first paper in the literature examining the extent to which a technology ownership impacts market outcomes and emissions.

Some seminal papers (e.g., Demsetz, 1983, Morck, et al. 1988) in financial economics investigated ownership issue. However, they mainly focused on firm performance or its market valuation with respect to who controls the firm. For example, Morck et al. (1988) examined the relation between the share of the firm owned by members of the board of directors and the firm's market valuation.

Several studies evaluate how firm ownership structure influences the performance in market settings. Lucking-Reiley and Spulber (2001) mention the likely impact of ownership structures in the electronic commerce and note that market power can impact the market performance. Yoo et al. (2007) theoretically examine an online marketplace in a two-sided network model to show that prices, market participation, and social welfare can differ under different ownership structures. They find that biased marketplaces (owned and managed by either buyers or sellers) entail higher surplus and lower prices for market participants compared to neutral marketplaces (owned by independent entrepreneurs).

In contrast to these papers, we explain the impact of ownership (i.e., a new production capacity comes online by either firm A or firm B) on market outcomes through the market structure, i.e., cost functions and the degree of competition in the market place. After we develop an ownership theory, as an application we focus on wind generation and examine how its ownership impacts market outcomes and the environment. The analysis could be extended to include solar power because wind and solar generations are assumed to have zero marginal cost of production. In particular, we investigate how wind generation

[2]Traber and Kemfert (2011), and Aydemir and Genc (2014) consider market power.

ownership affects CO_2, NO_x, and SO_2 emissions levels, market prices, generation levels of conventional technologies, and aggregate outputs in the Ontario power market. This research has important policy implications because the wind generation licenses are granted by regulatory agencies who decide which wind farms should be approved and provisioned into the network.

Most renewable energy projects (including wind and solar) in Ontario are required to obtain Renewable Energy Approval from the Ministry of the Environment (MOE).[3] These projects, depending on generator type and location, have to satisfy certain environmental, archaeological, heritage, and locational (proximity to the grid and municipality) requirements, and general public consultations.[4] Prior to submitting a renewable project to the MOE, it first goes to the Ministry of Natural Resources, and then the Ministry of Tourism and Culture, where it has to be reviewed and signed-off. In addition, if the project needs to be connected to the grid, it has to pass a Connection Impact Assessment provided by the system operator (IESO). Moreover, if new transmission lines are needed to connect renewable energy into the system, approval of Ontario Energy Board (under the Section 92 of the Ontario Energy Board Act, 1998) is required. In other provinces, application procedures are similar.[5] Wind project applications are often rejected by the regulators. For instance, 57% of proposed wind projects were rejected in the UK in 2014.[6]

Consequently, regulators and government officials have a direct role in choosing the firms running the wind generation facilities. As we show in this paper, ownership matters because the same amount of wind capacity under different firm ownership can lead to different market prices, outputs, and emissions. In particular we aim to answer the following questions: How does the adoption of green technologies affect the market prices

[3] Source: http://www.energy.gov.on.ca/en/archive/regulatory-approvals-and-permits. Only very small-scale wind, solar or biomass projects are exempt from the approval.

[4] These requirements are documented in detail at the Ontario Environmental Registry. Source: http://www.ebr.gov.on.ca/ERS-WEB-External/

[5] For instance, in the province of British Columbia approval of wind power projects is under responsibility of the Ministry of Forests, Lands, and Natural Resource Operations which manages the allocation of Crown land for wind power projects below 50 MW. For wind projects exceeding 50 MW, another regulator (The Environmental Assessment Office) examines and decides whether to give approval. Source: http://www.for.gov.bc.ca/land_tenures/tenure_programs/programs/windpower/index.html

[6] Source: http://www.theguardian.com/environment/2015/jan/21/six-in-10-uk-onshore-wind-farms-rejected-report

and outputs? What are the likely effects of increased wind capacity on the environment? How much does an increase in wind capacity reduce greenhouse gas emissions?

We observe that if the market is perfectly competitive then ownership would not affect prices and allocations. This result is called ownership indifference. However, when sellers have market power ownership of zero cost marginal cost technologies (such as wind/solar farms) matters and is critical to determine market prices, outputs and pollution levels. Using a dominant-firm with competitive fringe model we show that when the dominant firm owns new renewable capacity, output and welfare are lower than when competitive fringe firms own the same amount of new renewable capacity. The effect of renewable ownership on emissions is ambiguous, depending on the distribution of emissions rates across power plants. We extend the basic model to study the Ontario wholesale electricity market, using a dominant sector of three strategic (Cournot) firms coupled with a competitive fringe sector. In the Ontario context, we find that market outcomes under the largest firm's (Ontario Power Generation - OPG) ownership of wind farms are different than the ones under the smaller firm's (Brookfield Inc.) ownership. In particular, market prices are higher under OPG's wind generation ownership scenarios, while air emissions are higher under Brookfield's ownership. Also the rate of change of emissions (CO2, NOx, and SO2) is non-linear and shows variations over the ownership. These findings indicate that market power along with the degree of cost asymmetries between the firms drive the main results.

The structure of the paper is as follows. Section 2 introduces the theoretical model and proves that the ownership of low marginal cost technologies (such as wind turbines) can impact the market outcomes asymmetrically. Section 3 applies the model to the Ontario wholesale electricity market. The final section discusses the policy implications of the results.

2 Model

The ownership of renewable generation capacity does not affect market outcomes in a perfectly competitive market. Consumers and regulators are indifferent about who owns and operates a green technology. We refer to this result as, "ownership indifference in a competitive market". This is a straightforward implication of a supply and demand model. Adding any w units of renewable output (with zero marginal cost) will shift the aggregate supply curve to the right by w units regardless of who owns the renewable generation capacity. As a result of increase in supply, the market price goes down and quantity produced goes up.

Ownership of renewable capacity will matter when there is market power in the energy market. We explore the role of renewable ownership in the simplest possible model with market power: a model with one dominant firm and a competitive fringe sector.

Model Notation

$D(p)$ = wholesale market demand, as function of price p

$S(p)$ = competitive fringe supply of its non-renewable output, as function of price p

$C(Q)$ = dominant firm cost, as function of its non-renewable output Q

K^D = renewable capacity owned by dominant firm

K^C = renewable capacity owned by competitive fringe firms

f = capacity factor for renewables; $f \in (0, 1)$

For simplicity we consider market demand and fringe supply functions for a representative period (e.g., an hour) in the wholesale market. We assume that D is strictly decreasing, S is strictly increasing, and C is increasing and (weakly) convex. We assume renewable output is equal to renewable capacity times its capacity factor, where capacity factor is defined by average renewable output per unit of capacity. Additionally, we assume that the marginal cost of renewable energy generation is zero.

The dominant firm (DF) sets price to maximize its profit, taking into account the competitive fringe supply response to its pricing decision. The DF profit function is:

$$\pi(p, K^D, K^C) = p(D(p) - S(p) - fK^C) - C(D(p) - S(p) - fK^C - fK^D) \qquad (1)$$

The necessary condition for DF price-setting is (subscript indicates partial derivative):

$$\pi_p(p, K^D, K^C) = D(p) - S(p) - fK^C + [p - C'(D(p) - S(p) - fK^C - fK^D)](D'(p) - S'(p)) = 0 \tag{2}$$

Note that this necessary condition may be re-arranged to yield the standard optimal pricing result that equates the proportional markup of price over marginal cost to the inverse of the price elasticity of residual demand. We assume that the demand and fringe supply functions satisfy mild additional restrictions such that the second order condition for the DF is satisfied; i.e., $\pi_{pp} < 0$.

Next we examine how renewable ownership affects market outcomes. We can derive the effect of an exogenous change in either type of renewable capacity on the DF's optimal price by totally differentiating the necessary condition (2) with respect to price and the two renewable capacities. This yields

$$\frac{dp}{dK^C} = \frac{f[1 - (D' - S')C''(D - S - fK^C - fK^D)]}{\pi_{pp}} < 0, \tag{3}$$

and,

$$\frac{dp}{dK^D} = \frac{f[-(D' - S')C''(D - S - fK^C - fK^D)]}{\pi_{pp}} \leq 0. \tag{4}$$

Proposition 1 *An increase in renewable capacity owned by competitive fringe firms has larger price-reducing and output-increasing effects than an identical increase in renewable capacity owned by the dominant firm.*

The result follows directly from (3) and (4). An increase in K^C yields a horizontal rightward shift of the total fringe supply curve ($S(p) + fK^C$) and a corresponding leftward shift of residual demand. The DF reacts to this by reducing output, but by a smaller amount than the increase in fringe supply. As a result, total output rises and the market price falls, since the demand function is strictly decreasing. On the other hand, an increase in K^D shifts the marginal cost curve for *total output* of the DF for nonrenewable output rightward, but has no effect on residual demand. If the marginal cost function is increasing (i.e., $C''(\cdot) > 0$) then the DF will increase output and price will fall. Note however that the same effect is present when K^C increases, since in this case the DF also moves to a nonrenewable output with lower marginal cost. The difference between the impact of a change in K^C and K^D is highlighted for the case in which the marginal cost of nonrenewable output of the DF is constant (so that $C''(\cdot) = 0$). In this case, an increase in K^D results in a decrease in nonrenewable output of the DF that exactly offsets the increase in renewable output, so that total output and price are unchanged. An increase in K^C yields an increase in total fringe supply and the reaction of the DF results in an increase in total output and a lower price.

Proposition 2 *Marginal profit associated with an increase in renewable capacity is greater for competitive fringe firms than for a dominant firm.*

Marginal revenue associated with a change in renewable capacity is fp for a competitive fringe firm, since fringe firms are price takers and renewable capacity factor is f. The corresponding marginal revenue for a dominant firm is $fC'(Q)$; the price effect vanishes by the envelope theorem. The DF charges a markup of price over marginal cost, so fringe marginal revenue exceeds DF marginal revenue for renewable capacity. It follows that marginal profit for renewable capacity is greater for fringe firms than for the DF, as long as the marginal investment cost of renewable capacity is the same for both types of firms. Proposition 2 implies that competitive fringe firms would have a greater incentive to invest in renewables than a dominant firm with market power. Absent regulatory intervention regarding renewable investment, we would expect competitive fringe firms to invest in and own renewables rather than a dominant firm with market power.[7] However, in practice it is common for regulatory policies to be important drivers of renewable investment. Consider, for example, a renewable portfolio standard, which sets a minimum required total amount of renewable output for a market. In the context of our simple model, such a policy would also fix a minimum total amount of renewable capacity. Let $\Delta K > 0$ be the mandated

[7]This difference in profitability of additional renewable capacity is analogous to the replacement effect on profits associated with investment in a new technology. See the discussion in chapter 10 of Tirole (1988).

increase in renewable capacity, and let investment cost per unit of renewable capacity be equal to s (translated to a per period basis to conform to the demand and cost conditions of our model). If competitive fringe firms invest in the mandated additional renewable capacity then the impact on DF profit is:

$$\frac{d\pi}{dK^C} = \pi_p \frac{dp}{dK^C} + \frac{\partial \pi}{\partial K^C} = -f(p - C'(Q)) < 0 \tag{5}$$

Alternatively, if the DF invests in the mandated renewable expansion directly, its change in profit is:

$$\frac{d\pi}{dK^D} - s = \pi_p \frac{dp}{dK^D} + \frac{\partial \pi}{\partial K^D} - s = fC'(Q) - s \tag{6}$$

Note however that a mandated increase in renewables would likely require government subsidies. An investment subsidy (e.g., an investment tax credit) for renewables would have to yield a post-subsidy marginal cost of investment equal to the marginal revenue for renewable capacity for competitive fringe firms. That is, accounting for the renewable subsidy we have, $s = pf$, where we are interpreting s as the post-subsidy marginal investment cost of renewable capacity. Substituting for s into (6) yields:

$$\frac{d\pi}{dK^D} - s = \pi_p \frac{dp}{dK^D} + \frac{\partial \pi}{\partial K^D} - s = -f(p - C'(Q)) < 0 \tag{7}$$

Comparing conditions (5) and (7) we see that the impact of a mandated increase in renewable capacity on dominant firm profit is the same whether competitive fringe firms invest in and own the renewable capacity or the dominant firm does. In each case, the dominant firm sees a reduction in profit due to the mandated increase in renewable capacity. Since the reduction in profit is the same in both cases, a dominant firm would be indifferent between investing in and owning renewable capacity itself and having competitive fringe firms invest and own. This result could explain why a dominant firm with market power would invest in renewable capacity in spite of our result in Proposition 2 that competitive fringe firms would earn greater profit from investing in renewables.

The final part of this section analyzes the welfare impact of renewable ownership. We assume no income effects for energy so that we can use consumers' surplus as a welfare measure for consumers. We define welfare to be consumers' surplus plus producers' surplus, gross of renewable investment cost.

$$W(p, K^D, K^C) = \int_p^{\infty} D(x)dx + \pi(p, K^D, K^C) + \int_0^p [S(x) + fK^C]dx \tag{8}$$

If the damages associated with emissions from fossil fuel generation are internalized in the cost functions of the dominant firm and fringe firms - e.g., via optimal emissions fees - then this welfare function incorporates emissions damages. Otherwise, $W(\cdot)$ should be interpreted as welfare gross of emissions damages.

Proposition 3 *Welfare increases more if competitive fringe firms invest in renewable capacity than if the dominant firm does.*

Proof: First, note that the change in welfare associated with a price change is:

$$W_p(p, K^D, K^C) = -D(p) + \pi_p + S(p) + fK^C = -D(p) + S(p) + fK^C < 0 \tag{9}$$

We assume that price is chosen by the DF to maximize its profit, so the π_p term in the expression above is equal to zero. W_p is equal to the negative of total output for the dominant firm. The next step is to find the change in welfare associated with a change in renewable capacity owned by competitive fringe firms,

$$\frac{dW}{dK^C} = W_p \frac{dp}{dK^C} + W_{K^C}$$

$$\frac{dW}{dK^C} = [-D(p) + S(p) + fK^C]\frac{dp}{dK^C} - f(p - C'(D(p) - S(p) + fK^C + fK^D)) + fp$$

$$\frac{dW}{dK^C} = [-D(p) + S(p) + fK^C]\frac{dp}{dK^C} + fC'(D(p) - S(p) + fK^C + fK^D)$$

and owned by the dominant firm,

$$\frac{dW}{dK^D} = W_p \frac{dp}{dK^D} + W_{K^D}$$

$$\frac{dW}{dK^D} = [-D(p) + S(p) + fK^C]\frac{dp}{dK^D} + fC'(D(p) - S(p) + fK^C + fK^D)$$

The two expressions for welfare change are identical except for the price effect terms. Since $W_p < 0$ and since $dp/dK^C < dp/dK^D \leq 0$ by Proposition 1, we have shown the result. $\square$

It is important to note that the ownership of new renewable capacity can also affect emissions. Differing amounts of non-renewable output produced by the DF and fringe firms will be displaced depending on the ownership of new renewable capacity, and this will lead to differing emissions reductions. In the application we estimate the impact of alternative renewable ownership on emissions. This points to a qualification of our welfare result in Proposition 3. If firms' cost functions do not internalize emissions damages then there will be additional welfare effects associated with the impact of renewable ownership on emissions. We do not pursue a formal analysis of welfare effects associated with changes in emissions here, but we do consider these welfare effects in our application.[8]

3 Application to the Ontario Electricity Market

In this section we aim to quantify the impact of renewable capacity ownership on market performance. For this reason we study the Ontario wholesale electricity market and run several wind ownership scenarios to show how different firm ownerships of new wind farms impact the Ontario market prices and emissions. In particular, we employ a model of Ontario wholesale electricity market similar to the one developed by Aydemir and Genc (2014). They model competition in the Ontario market by examining power portfolios of firms along with generation costs of all generators. They construct marginal cost curves using financial data (amount spent on fuel and permit prices) and technical characteristics of generators (heat rates, emission rates), and hourly availability and production capabilities of all generators for each hour of the day in a year. They also estimate the hourly market demand curve. Before the hourly market clears they update the model parameters,

[8] See Baker, et al. (2013) for a formulation of the marginal social value of renewable capacity that incorporates emissions effects.

and estimate the cost functions and demand curve, and then run a capacity constrained Cournot firms with fringe suppliers model to predict the hour-ahead market price and production quantities of strategic and non-strategic firms. Specifically, they assume that Ontario Power Generation Inc, Bruce Nuclear Inc, and Brookfield Renewable Energy are Cournot competitors and the rest of the generators/firms are competitive fringe. Using detailed data sets covering 2007-2008 they find that the model generates actual market prices and outputs with high accuracy.

Although our theoretical model involves, by purpose, the simplest competition model of market power (a dominant firm a competitive fringe) to show the impact of ownership, the actual market is far from this setting. In the simulation model, which is a representative of Ontario wholesale electricity market, there are a few Cournot firms facing competitive fringe sector. Therefore, the simulation model is an extended version of the theoretical model.

To measure the impact of ownership on market outcomes we employ data sets which are comprised of detailed plant level and market data provided by the Environment Canada and the Independent Electricity System Operator (IESO). They include hourly export/import quantities, hourly actual production and available capacity for each generator, hourly market clearing price and demand quantity. In addition, we use costs (such as fuel prices, emissions permit fees) and generator characteristics data (such as emission rate, heat rate, age, and fuel type) as described in detail below.[9] In Table 1, we tabulate the generation characteristics of all plants, incorporating plant type, number of plants for each type, total installed capacity, fuel type, average heat rates, as well as emission rates, reported by the Environment Canada.[10] For our model calibrations, we employ data in this table which represents over 560 generators fueling wood, coal, natural gas, diesel, oil, waste gas, uranium, and renewables (hydro and wind). Note that the composition of generation assets

[9]Similar data sets have also been used by Genc (2016) for estimating price elasticity of demand in the Ontario market.

[10]The Environment Canada provides the list of all generators in the country. It is called the Canadian Module Unit List which is a fundamental modeling input to the Canadian IPM Base Case 2004. It is an inventory of all currently operating/existing electric generating units (EGUs) and planned-committed units and their relevant characteristics. The web-link for the reference is http://www.ec.gc.ca/air/default.asp?lang=En&n=D6C16D01-1.

in Ontario has gradually changed with the Cleaner Air Act and all coal-fired generators were shut down as of mid-2015.

Table 1: Characteristics of Ontario Power Plants

Plant Type	N.of Plants	Tot. Capacity (MW)	Average Heat Rate(kJ/kWh)	Average NOx Rate(g/MJ)	Average SO2 Rate(g/MJ)	Fuel Used
Biomass - Wood\Wood Waste	14	271	9395	0.1	0	Wood\Wood Waste
Coal with Catalytic Reduction and SO2 Scrubber	2	980	9849	0.02	0.03	Eastern U.S. Bitum
Cogeneration -Combined Cycle	18	1585	8574	0.07	0	Natural Gas
Cogeneration -Combustion Turbine	29	308	10513	0.04	0	Natural Gas
Cogeneration - Oil/Gas	19	224	9648	0.1	0	Natural Gas
Combined Cycle	5	748	10614	0.04	0	Natural Gas
Combustion Turbine	65	251	14263	0.04	0	ON Diesel, Natural G
Combustion Turbine	2	24	14,289	0.04	0	Oil
Combustion Turbine	3	21	14,289	0.04	0	Natural Gas, Oil
Fossil - Other	3	21	6267	0.15	0	Refinery Gas
Fossil - Other	1	4	6267	0.15	0	Blast Furnace Gas
Hydro	339	7627	0	0	0	Hydro
Landfill Gas	5	9	11606	0.11	0	Landfill Gas
Nuclear	18	12278	11220	0	0	Uranium
Oil/Gas Steam	2	6	11197	0.1	0	Natural Gas
Oil/Gas Steam	4	2140	10249	0.12	0.05	Natural Gas, Oil
Other	4	99	11606	0	0	Waste Gas
Pumped Storage	6	174	0	0	0	Hydro
Unscrubbed Coal Catalytic Reduction - Bituminous	2	980	9890	0.02	0.4	Eastern U.S. Bitum
Unscrubbed Coal-Bituminous	12	5013	9890	0.22	0.57	Eastern U.S. Bitum
Unscrubbed Coal-Lignite	3	525	11056	0.14	0.43	Saskatchewan Lignite
Wind	7	17	0	0	0	Renewable
Total	563	33305				

The theory section covered a setting without specifying functional forms of demand, supply, and cost functions. For the Ontario market simulations, we employ specific functions estimated by Aydemir and Genc and deal with the generators characterized in Table 1. Following them, we assume an affine inverse demand curve, $D(p) = a - bp$, where quantity demanded is the summation of export demand and the Ontario market demand and p is the hourly market price called "Hourly Ontario Energy Price (HOEP)". In our market calibrations, the demand coefficients (a,b) change for every hour as in reality demand conditions change based on temperature and time of day. The demand parameters are estimated based on a approach described in Aydemir and Genc, who pinpoint an affine demand curve passing through the actual market price and quantity for a given level of price elasticity of demand.

We construct and estimate the cost functions for every hour in the study period. First, we construct the total marginal cost of production for each generator using fuel consumption quantity, dollar amount spent, energy content of the fuel data, emissions rates and emissions permit prices.[11] The marginal fuel cost of a generator is calculated by the following formula:

Marginal Fuel Cost of a Generator = Heat rate (in kj/kwh) * ($dollar spent on fuel)/[total fuel consumption * Energy content (in kj/kg)][12]

As emission permits are traded for NOx and SO2 gasses in Ontario[13], the marginal emission costs for a generator is calculated by:

SO2 marginal emission cost for a generator = Heat rate of generator * SO2 rate of generator * price of SO2 emission permit

[11] The marginal cost data incorporating fuel consumption, dollar spent and energy content of a fuel is provided by Statistics Canada (source: Statistics Canada (2009) Electric Power Generation, Transmission and Distribution – 2007, Catalogue no. 57-202-X).

[12] Instead of using the actual dollar amounts spent for a fuel, as an alternative marginal fuel cost formulation we have used the spot fuel prices directly. The results are robust to the marginal fuel cost formulations (see Aydemir and Genc).

[13] See Ontario Emissions Trading Registry at http://www.oetr.on.ca/oetr/faq/faq.jsp

NOx emission cost for a generator = Heat rate of generator * NOx rate of generator * price of NOx emission permit.

The total marginal cost for a generator will then be the summation of marginal fuel cost, SO2 marginal emission cost, and NOx marginal emission cost.

After obtaining the total marginal cost for a generator, we construct hourly aggregate marginal cost of a firm using its all available generators and their available capacities. Consequently, Ontario Power Generation (OPG) has over 60 generators with production technologies of hydro, nuclear, coal, and natural gas. Its estimated cost function is cubic, $C_1(Q) = a_0Q^3 + a_1Q^2 + a_2Q + a_3$. Bruce Power runs only nuclear plants with the same heat rates and its estimated cost function is linear, $C_2(Q) = c_2Q$. Brookfield Renewable has a two step cost function: The first step is due to its hydro and wind generators with the cost function , $C_3(Q) = c_{31}Q$, if $Q \leq K_{31}$ (production less than or equal to available capacity for a given hour), and the second step is due to its natural-gas fired generators (with the same heat rates) $C_3(Q) = c_{32}Q$, if $K_{31} < Q \leq K_{31} + K_{32}$, where all cost coefficients are non-negative. The fringe firms have various types of production technologies and their aggregate supply function is estimated by $S(p) = a_f + b_f p$. The fringe supply is also capacity constrained, $S(p) \leq K_f$. Note that in all market simulations below, we estimate all cost function coefficients hourly. That is, the cost coefficients change hourly. Also, instead of installed production capacities, we use hourly available capacities (which are different than the installed capacities reported in Table 1) which change from hour to hour for almost all generators (including nuclear and hydro) in the data set. Therefore, cost functions will change due to generators' availability (on or off due to maintenance/failure), their available production capacities (due to ramp up/down rates), and change in fuel costs.

The residual demand faced by the Cournot firms will be $D_R(p) = D(p) - S(p) - I(p)$, where $I(p)$ is the aggregate import function.[14] In the simulations we assume that imports

[14]There are many small power importers and electricity is imported from the adjacent markets (such as New York, Michigan, Minnesota, Quebec, Manitoba).

are exogenous, that is, $I(p) = \overline{I}$. This is because the imports are scheduled ahead of time (that is, at the time of market clearing all market players observe the scheduled or actual import quantity). The objective for each strategic firm i is to choose output so as to maximize its profit subject to production constraints for each hour. That is,

$$\begin{aligned} max\, \pi_{i,t} &= p_t(Q_t)q_{i,t} - c_{i,t}(q_{i,t}) \\ s.t. \quad & 0 \leq q_{i,t} \leq K_{i,t} \end{aligned}$$

where the cost functions and demand are defined as above. The aggregate output at time t is $Q_t = q_{i,t} + q_{-i,t} + S_t + I_t$, where $q_{-i,t}$ is the total output of firm i's strategic rivals.

In the following table, Table 2, we report actual output/capacity by firm and technology ownership of the firms in Ontario during the study period. Based on it, some concentration indexes (such as HHI and RSI) can also be calculated. There are about 100 small generators owned by small firms and/or entrepreneurs (fringe suppliers). From the table, it is clear that per firm capacity is less than 10 MW for fringe firms, which are assumed to be perfectly competitive, and the rest of the firms (i.e., OPG, Bruce, and Brookfield) are assumed to have market power, given their market shares and technology mix. With this assumption, Aydemir and Genc (2014) show that the simulation outcomes (prices and outputs) are very close to the actual ones.

In calculating the quantity of emissions, we use each generator's NOx and SO2 rates (g/MJ) as well as the heat rates (kj/kwh), provided in Table 1. We multiply a generator's emission rate with its heat rate (and a conversion rate) to find emissions released per unit of electricity production (MWh). NOx releasing production technologies use diesel, refinery gas, wood and wood waste, landfill gas, coal (lignite, bituminous, sub-bituminous), natural gas, oil. Among those technologies, coal (lignite, bituminous, sub-bituminous) plants are the main source of SO2 emissions.[15] As the CO2 rates of Ontario generators

[15] According to the Environment Canada (2004) Canadian Module Unit List, SO2 rates of all natural-gas fired plants in Ontario are zero.

Table 2: Firm Level Actual Average Output (q)-Available Capacity (K) Profile

Technology	OPG	Bruce Nuc	Brookfield	Fringe_total
Hydro_q (MWh)	3206	-	112	95
Hydro_K (MW)	5688	-	662	274
Wind_q	-	-	70	36
Wind_K	-	-	189	130
Natural Gas/Oil_q	89	-	48	172
Natural Gas/Oil_K	1365	-	59	254
Nuclear_q	4512	3929	-	-
Nuclear_K	4539	4040	-	-
Coal_q	3029	-	-	-
Coal_K	4034	-	-	-
Biomass_q	-	-	-	129
Biomass_K	-	-	-	188
All_Tech_q (MWh)	10836	3929	230	432
All_Tech_K (MW)	15626	4040	910	846

Notes: K is the available capacity per hour.
Fringe_total refers to total fringe output.
- refers to not available.

were not reported by the Environment Canada in Table 1, we use the U.S. plant data sets (reported at the EPA 2007 eGrid document) to estimate the CO2 rates of natural gas, coal (bituminous, sub-bituminous, and lignite), diesel fuel oil, and wood and wood waste fired generators. Also, note that in Table 1 only coal plants have SO2 rates recorded. The SO2 rates of natural gas plants are zero in the dataset. We suspect that SO2 rates of natural gas plants are negligible (near zero) because of highly efficient generators.

Before we run our counterfactual wind capacity expansion scenarios, we compare model predictions to actual market outcomes in Table 3. We run the model for every hour of Fall, September through November 2007, during which we also run our ownership simulations for the reasons we explain below.[16] Table 3 shows that the distribution of our predicted prices (the lowest price, the highest price, skewness, and the standard deviation) is near

[16]We employ Argonne National Lab NEOS server PATH solver in the AMPL environment. We formulate the market equilibrium conditions as complementarity problems taking into account of production capacity constraints as well as the non-negativity conditions. The PATH solver is known to be the state-of-the-art solver for solving market equilibrium models. The solver provides the equilibrium outputs of all firms for every hour.

Table 3: Summary Statistics: Actual versus Model Outcomes

	Actual Market	Model Prediction
Demand Quantity (MWh)		
mean	17,791	17,071
st.dev.	2,119	2,060
min	12,807	1,100
max	24,117	22,571
Price ($/MWh)		
mean	46.85	49.68
st.dev.	21.83	22.71
skew.	1.41	1.33
min	-0.40	-1.01
max	297.52	295.50
Total Emissions (tons)		
NOx	9828	4776
SO2	25968	11208
CO2	7942254	5515073
n (hours)	2184	2184

the distribution of actual prices, confirming the predictive power of the model. We observe similar accuracy for the market demand/supply distribution. Exceptions arise for the prediction of the lowest level of market demand and the total emissions. Normally, at a negative price the Cournot model should predict zero output. At the negative minimum price of -1.01, firms prefer not to produce but the minimum supply of 1100 MWh mainly comes from importers whose price is different than the market price. In some actual electricity markets, at the negative market price some wind and solar generators also supply electricity into the grid because their price is subsidized at a fixed rate irrespective of market price. As expected our emissions estimations are lower than the actual emissions, because the fuel mix predicted by the model is off. This stems from the profit maximization problem (defined above) which finds the optimal aggregate output for each firm for each hour. We then distribute this total output per firm in merit order, from least costly generation units to most costly generation units. Furthermore, i) we do not consider network constraints which can impact the actual generations; ii) our estimated total generation which is lower than the actual output also explains lower emissions; iii) we do not consider some constraints such as ramp-up and ramp-down constraints as well as the start-up costs which all impact the actual generation dispatch decisions.

Given that the Green Energy Act of Ontario strives to foster wind (and solar) energy investment and production, we focus on wind generation (as solar has a small potential in Ontario) and simulate the Ontario market model by incrementing wind capacity to assess how market prices and emissions change in equilibrium. We choose the most windy months -September, October, November- of 2007 as a study period during which wind generation levels and the wind capacity utilization rates are the highest in Ontario. In simulations we assume that wind output in any given hour is equal to its actual capacity factor for that hour times total wind capacity. Also, we assume that hydro generators in the system will produce at their actual outputs because of the short and long term hydropower management issues and constraints.

In our study period only Brookfield Energy and fringe producers owned wind turbines among other production technologies. Therefore, we initially run the market model to investigate the impact of extra wind generation by Brookfield. In the counterfactual scenarios we increase the actual wind output of the firm proportional to the wind-farm capacity investments defined below. We also examine a counterfactual scenario that OPG would own and run the new wind farms. This scenario has materialized in the following years obeying the Green Energy Act of Ontario, which allowed OPG (the largest producer, which is a Crown Corporation) to add renewable generation assets (mainly wind) to its power portfolio. Since 2010 OPG has been producing electricity from its wind turbines. These calibrations will allow us to quantify the impact of ownership structure.

During the study period, in 2184 hours of Fall 2007, the average installed wind capacity is 318 MW (denoted by $\omega = K$). However, the available capacity has changed over the hours of study period due to maintenance/failure and new wind capacity installments. Consequently, the minimum available capacity is 198 MW and a maximum of 373 MW . The actual total wind output is on average 106 MWh with a minimum of 0 MWh and a maximum of 296 MWh. Clearly, both wind output and the available production capacity are intermittent due to wind speed and technological reasons. For each hour we compute a capacity factor (total production divided by total capacity in the system). The system capacity factor is on average 0.33 with the standard deviation of 0.23. The maximum capacity factor is 0.95 and the minimum is 0. We consider two wind capacity expansion scenarios/counterfactuals which are congruent with the future investments implied by the Green Energy Act: i) the existing wind capacity increased by additional 600 MW (denoted by $\Delta\omega = 2K$), which corresponds to almost adding two times the average available capacity into the system; ii) the existing wind capacity increased by additional 1200 MW (denoted by $\Delta\omega = 4K$), which corresponds to adding almost four times the average installed capacity into the system. That is, the scenarios consider realizations of 600 MW and 1200 MW new capacity additions, respectively, into the market. To figure out hourly additional wind outputs due to the new capacity expansion scenario, we multiply the hourly changing system capacity utilization rate (i.e., capacity factor) with the new capacity. In fact, to account for wind generation intermittency, we obtain hourly new wind output levels based on observed hourly capacity factors. The impact of these new investments on wind output distribution is presented in the following table.

Given these wind investment counterfactuals we examine the wind ownership scenarios of Brookfield and OPG. We present our ownership results in Table 5, where predicted firm level productions, market quantity and price distributions, and aggregate equilibrium emissions in Fall are reported. We add extra wind output stemming from the wind invest-

Table 4: New Wind Investments and Generation

	$\omega = K$	$\Delta\omega = 2K$	$\Delta\omega = 4K$
Wind output, MWh:			
mean	106	200	401
st.dev.	74	140	279
min	0	0	0
max	296	568	1135

ment scenario described above into the production portfolio of a firm and run the model for each hour of Fall 2007 (in total 2184 hours) to obtain equilibrium productions. We distribute the firm aggregate output over its generators in merit order (the least costly manner) and then calculate NOx, SO2 and CO2 amounts (in ton) released by each generator by multiplying heat rate, emission rate and generation quantity. We next aggregate the emissions over hours of study period and generators of a firm. The market impact of firm's ownership of a new wind farm is examined with the scenario $\Delta\omega = 2K$ (proportional wind generation increase for every hour due to doubled investment)and the scenario $\Delta\omega = 4K$ (wind production increase due to quadrupled capacity expansion). Note that these wind generation expansions and the resulting wind outputs are small relative to market demand and total productions, are also conformable with the future actual wind (investments and) productions. The current market structure is represented by $\omega = K$, referring to model simulation using all existing available production technologies.

In Table 5, we do not report any emissions for Bruce Nuclear, because it does not emit any NOx, SO2 or CO2 according to the Environment Canada. Technically nuclear plants may release some carbon dioxide; because its rate is very small all researchers, to our knowledge, neglect nuclear plants' CO2 emissions. Also, for all wind generation scenarios the amount of SO2 released by Brookfield and fringe suppliers are zero because their generators' SO2 rates are zero according to Environment Canada, as listed in Table 1. As expected, in Table 5, the equilibrium NOx and SO2 emissions (in ton) are very low relative to the amount of CO2 emissions.

Several key results emerge from the model simulations. We find that extra wind generation improves efficiency (lower prices and higher consumption) and reduces emissions of all gasses for all firms irrespective of ownership. However, the rates of emissions reductions are nonlinear. That is, the impact of each MWh wind generation has different effects on prices and outputs (and therefore emissions) depending on the wind scenario (level of wind capacity) as well as on the ownership. For instance, when the wind capacity investment doubles (scenario $\Delta\omega = 2K$) the average market price goes down by 1.1% (drops from \$49.68 to

Table 5: Simulated Descriptive Statistics

	Brookfield Ownership			OPG Ownership		
Wind increase	$\omega = K$	$\Delta\omega = 2K$	$\Delta\omega = 4K$	$\omega = K$	$\Delta\omega = 2K$	$\Delta\omega = 4K$
Quantities (MWh):						
Q_{Demand}	17071	17199	17326	17071	17152	17267
q_{OPG}	9404.9	9374.9	9348.4	9460.6	9551.1	9679.6
q_{Bruce}	4035.9	4035.9	4035.8	4035.9	4034.1	4035.4
q_{Brook}	760.3	958.9	1156.8	760.3	761.4	759.6
q_{Fringe}	1691.5	1676.7	1661.8	1691.5	1675.9	1668.9
Price ($/MWh):						
p	49.68	49.15	48.62	49.68	49.15	48.89
st.dev.(p)	22.71	22.53	22.35	22.71	22.51	22.52
skew.(p)	1.33	1.32	1.32	1.33	1.36	1.34
Emissions by Firm (ton):						
Total OPG Emissions						
NO_x	2998	2870	2752	2998	2789	2658
SO_2	11208	10778	10369	11208	10418	9938
CO_2	3673803	3559201	3447235	3673803	3459452	3309023
Total $Brook$ Emissions						
NO_x	41	38	35	41	39	40
SO_2	0	0	0	0	0	0
CO_2	36878	34870	32008	36878	35527	36048
Total $Fringe$ Emissions						
NO_x	1737	1718	1699	1737	1716	1708
SO_2	0	0	0	0	0	0
CO_2	1804392	1787669	1770809	1804392	1786787	1778941
Total Emissions (ton):						
NO_x	4776	4626	4486	4776	4544	4406
SO_2	11208	10778	10369	11208	10418	9938
CO_2	5515073	5381740	5250052	5515073	5281766	5124012
n (hours)	2184	2184	2184	2184	2184	2184

$49.15) under Brookfield ownership, and falls by almost the same amount under OPG ownership (although equilibrium prices under Brookfield ownership are different than the prices under OPG ownership for every hour). However, when the wind production further increases proportional to the new investment of $\Delta\omega = 4K$ (from $\Delta\omega = 2K$ to $\Delta\omega = 4K$), the average market price falls by 1.08% (drops from $49.15 to $48.62) under Brookfield ownership, it decreases by 0.53% (drops from $49.15 to $48.89) under OPG ownership. Clearly, consumers enjoy lower prices and higher consumption under Brookfield ownership. Also, although price volatility (measured by standard deviation) seems to slightly go down under either firm's ownership for all wind capacity expansions, price spikes (measured by skewness) tend to be higher under OPG ownership across all wind scenarios. Note that while the change in market prices and outputs are small because of lower wind penetration into the system relative to the size of market, the changes in emissions are still sizeable.

In terms of predicted production, OPG meets more than half of market demand, and Bruce meets about a quarter of it. This is also true of their actual production. Therefore, firm-level model output predictions are near the actual productions. Moreover, while Brookfield's new wind facility increases its total output roughly at the rate of new wind generation, OPG withholds a substantial amount of conventional generation output when it adds wind capacity. For example, when Brookfield increases its average wind generation by 200 MWh, its average output increases by roughly the same amount (from 760.3 to 958.9 MWh). However, OPG only increases its average total output by 91 MWh (from 9460.6 to 9551.1 MWh) when its wind units facilitate on average 200 MWh output. Furthermore, under Brookfield ownership while Brookfield increases its total output at the average additional wind output, OPG reduces its total output 15% of the average wind production hike. However, under OPG ownership while OPG slowly increases its total output stemming from its zero marginal cost new wind output, Brookfield keeps its production steady (in the neighborhood of 760 MWh). These results are due to OPG's market power and Brookfield's high share of renewables.

The net benefit of increased wind generation is always positive for emissions. The total

CO2 in Fall decreases about 2.42% (from 5,515,073 to 5,381,740 tons) under Brookfield ownership and about 4.23% (from 5,515,073 to 5,281,766 tons) under OPG ownership when the average wind output increases by 200 MWh (that is from $\omega = K$ to $\Delta\omega = 2K$). When the average wind production further increases by 400 MWh every hour (that is from $\Delta\omega = 2K$ to $\Delta\omega = 4K$), aggregate CO2 emissions drop by 2.45% under Brookfield ownership and about 2.99% under OPG ownership. With new wind farm production OPG displaces more of its high-cost coal-fired plants. On the other hand, with new wind production Brookfield displaces a too little gas-fired generation. This is because its market share is small (therefore, increases its total output at the rate of new wind production) and has more efficient gas turbines than OPG has. Consequently, under OPG's wind ownership the electricity market produces less greenhouse gas emissions and is therefore much beneficial to the society for the sake of clean air. In terms of NOx and SO2 emissions, the environmentally congenial solution is again the OPG's ownership of new wind farms.

Based on the emission figures in Table 5, one can easily calculate average emission savings associated with extra wind generation in Ontario. For instance, when the change in average wind output is 200 MWh (from $\omega = K$ to $\Delta\omega = 2K$), we find that average CO2 emission saving is 0.53 ton per MWh wind generation per hour under OPG ownership. It is 0.31 ton per MWh wind output per hour under Brookfield ownership. For NOx emissions, the saving rate is 1.17 lbs with OPG ownership, and it is 0.76 lbs with Brookfield ownership. For SO2 emission, the saving rate is 3.99 lbs with OPG ownership, and it is 2.17 lbs with Brookfield ownership. These results show that ownership of renewables matters for environmental targets set by regulators and policy makers. Furthermore, OPG is about 50% more effective than Brookfield in terms of emissions reductions of CO2, NOx, and SO2.

Governments give large subsidies to wind/solar energy producers through feed-in-tariff programs with the expectation that air quality will improve. This is borne out in our simulations of the effect of increasing wind capacity in the Ontario wholesale market, where greater wind generation yields lower emissions of SO2, NOx and CO2. However, we show that incremental air quality improvements are smaller for successive increments in wind capacity. Most importantly, we show that the ownership of new wind capacity has an effect on both market prices and emissions reductions. This points to ownership of renewables as a factor that regulators and policy-makers should take into account when designing renewable energy policies aimed at reducing fossil fuel emissions in the electricity sector.

4 Conclusions

In this paper we examine the impact of ownership of a new production technology on market outcomes. Specifically, we focus on a current phenomenon of green technology production (e.g., wind farm energy generation) and address whether it matters which firms own and operate them. Our theoretical findings indicate that the ownership affects market outcomes in imperfectly competitive markets. As an application we utilize a detailed Ontario wholesale market model and quantify the impact of different ownership structures. Although we focus on wind ownership scenarios in the Ontario market, the results should also be valid for solar energy investments/productions as wind and solar generators are assumed to be zero marginal cost technologies. Moreover, our results can be generalized to other power market settings because in many electricity markets firms have market power and their production technologies are heterogeneous and incorporate renewables.

An important finding of this paper is that the ownership of wind turbines impacts firm and market performance as well as air quality. Even though it is the zero marginal cost technology, the market outcomes under OPG ownership of wind farms are different than those under the Brookfield ownership. It is clear that emissions and market prices nonlinearly decrease in wind generation. However, the amount of emissions is affected not only by who operates the new wind turbines but also how much electricity is produced by the wind generators.

A policy implication of our results is that regulators and policy makers should be careful about allocating green certificates (i.e., the rights to operate green technologies).

From the Ontario power market analysis we learn that *a*) because the market prices are lower, the wholesale electricity buyers benefit if the smaller firm, Brookfield, operates the new wind farms; *b)* however, because emissions of all gasses are lower for all wind scenarios, society enjoys better air quality under the OPG ownership; *c*) total emissions (CO2, NOx, S02) reduce in wind generation relative to no wind production, but the rate of change of emissions reductions differ depending on the ownership and the wind generation capabilities; *d*) the impact of each MWh wind power production has different effect on the emissions. However, in aggregate the wind generation improves the air quality over the course of periods.

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