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Highlights

- It does not matter who owns a new low-cost technology in perfectly competitive market.
- Capacity ownership will matter when there is market power in the market.
- In contrast to previous papers, we explain impact of ownership on outcomes through market structure.
- We show that ownership of new wind capacity impacts market prices and emissions.
- Regulators and policy-makers should take this into account when designing renewable energy policies.

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

Talat S. Genc† Stanley S. Reynolds‡

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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 measure the impact of renewable energy penetration into electricity markets and examine how the ownership of renewable capacity changes market outcomes (prices, outputs, emissions). As current public policies influence renewable energy ownership, this research provides useful insights for policy makers. We show how and why ownership of renewable capacity matters when there is market power in energy market. We apply our findings to the wholesale electricity market in Ontario, Canada, to analyze the impact of different ownership structures for wind capacity expansions. Using both simulation analysis and empirical analysis of market data, we show that the price-reducing effects of wind expansion are smaller when a larger strategic firm owns new wind capacity. Lastly, we show that the effect of wind ownership on emissions depends on both the amount of generation displaced by wind output and the emissions rate of displaced generation.

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 are 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 Ontario's Green Energy Act the government 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 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.[1] In essence we address the following question: if a fixed amount of renewable energy capacity is added into the system, would it matter whether firm A or firm B owned this new capacity? Specifically, how does the ownership of green technologies impact market outcomes and air quality, in particular wholesale prices, outputs, producer and consumer surplus, NOx, SO_2, and CO_2 emissions?

Many jurisdictions 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 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. Numerous states in the U.S. have renewable portfolio standards that set minimum shares of electricity generation from renewable sources. The global electricity supply by wind generation in 2020 is expected to be 8-12% of the total supply.[2]

A number of studies have examined the impact of wind generation on outcomes such as emissions, market prices, outputs of conventional generators, hydropower storage, power trade, and investment

[1]As pointed out by a referee, wind generation ownership also matters in the context of renewables auctions in which participation of small bidders is favored. This is what is observed in the UK and Ontario (see also footnotes 3 and 6).

[2]See http://www.gwec.net/global-figures/wind-in-numbers/ In Europe, as pointed out by a referee, all the EU member states have to comply with the "Renewables Directive" which sets binding targets for renewables at the country level.

incentives; Denny and O'Malley (2006), Benitez et al. (2008), Callaway and Fowlie (2009), Traber and Kemfert (2011), Cullen (2013), Rubin and Babcock (2013), Novan (2015), Genc and Aydemir (2017). Studies by Cullen (2013) and Novan (2015) provide empirical estimates of emissions reductions due to increases in wind generation. Other studies examine the extent to which increases in wind capacity depress wholesale energy prices; this is the so-called merit order effect: Acemoglu, et al (2017), Cludius, et al (2017), Traber and Kemfert (2011). Acemoglu, et al analyze a theoretical model of a wholesale electricity market with symmetric Cournot suppliers of conventional generation and renewable generation capacity that may be owned by either the Cournot suppliers or 'outside' non-strategic firms. They show that the merit order effect holds in their model and that shifting ownership of a fixed amount of renewable capacity toward strategic Cournot suppliers yields higher wholesale prices and lower welfare. The present paper also examines renewable capacity ownership effects, utilizing a different theoretical model and providing quantitative results from an application.

Several studies evaluate how firm ownership structure influences the performance in different 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 ownership affects CO_2, NOx, 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 wind generation licenses are often 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. 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 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 market prices 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 model with asymmetric Cournot firms and a competitive fringe, we show that when a strategic firm owns new renewable

[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

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 and apply it to study the Ontario wholesale electricity market, using a dominant sector of three asymmetric 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 those under a 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 (CO_2, NOx, and SO_2) is non-linear and shows variations over ownership allocations. These findings indicate that market power and the degree of cost asymmetries between firms drive the main results.

The structure of the paper is as follows. Section 2 introduces the theoretical model and shows how the ownership of low marginal cost technologies (such as wind turbines) can impact the market outcomes asymmetrically. Sections 3 and 4 describe the Ontario wholesale electricity market and explain how model parameters are determined. Section 5 reports simulation results. Section 6 extends the model for sensitivity analysis. Section 7 covers an empirical analysis to quantify the impact of renewable energy ownership on prices and emissions in Ontario using a recent data set. 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 which suppliers own and operate 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.

Acemoglu, et al (2017) explore the ownership issue using a model with two types of firms: symmetric and strategic Cournot suppliers versus non-strategic, price-taking renewable energy suppliers.

Cournot firms in their model have identical costs of thermal generation and identical amounts of renewable energy (or, capacity). They show that the equilibrium price is non-increasing in the total amount of renewable energy and, that the equilibrium price is increasing in the share of renewable energy owned by Cournot (i.e., strategic) firms.

While the symmetry assumption yields a tractable theoretical model, symmetry is a strong and possibly unrealistic assumption when applied to wholesale electricity suppliers. In this section we analyze a model with two asymmetric strategic Cournot firms and a competitive fringe of non-strategic firms. Both strategic and non-strategic firms have thermal generation capacity and renewable energy in our formulation.[7] We focus on a model with linear demand and fringe supply functions. Clear results for asymmetric duopoly are difficult to obtain for general demand, fringe supply, and cost conditions. Moreover, we use linear demand and fringe supply in our Ontario wholesale market application.

Wholesale market demand is, $D(p) = a - bp$, where p is the market price and a and b are demand parameters. Strategic firm i has thermal generators with increasing, twice-differentiable, convex cost function $C_i(q_i)$ for thermal output q_i. Strategic firm i also produces renewable energy R_i. Competitive fringe firms have supply function for thermal output, $S_f(p) = a_f + b_f p$, where a_f and b_f are supply parameters, and renewable energy R_f. Renewable energy is produced at zero marginal cost. Total renewable energy is, $R = R_1 + R_2 + R_f$. Let $\overline{R} \equiv (R_1, R_2, R_f)$ be the vector of renewable energy.

Strategic firm i competes by choosing the amount of thermal energy supply, q_i (all renewable energy is assumed to be supplied to the market). The inverse residual demand function is, $p = g - hR - hQ$, where $Q = q_1 + q_2$ and inverse demand parameters are given by $g \equiv (a - a_f)/(b + b_f)$ and $h \equiv 1/(b + b_f)$. Profit for firm i is,

$$\pi_i = p(q_i + R_i) - C_i(q_i) = (g - hR - hq_1 - hq_2)(q_i + R_i) - C_i(q_i). \tag{1}$$

There is a unique Nash equilibrium for our formulation of this asymmetric duopoly model; see Amir (1996). Equilibrium thermal outputs satisfy (for an interior equilibrium),

[7]Here, thermal generation refers to dispatchable generation. In our application we include hydro and nuclear generation as well as fossil fuel generation in the dispatchable category. See Joskow (2011) for a discussion of dispatchable versus renewable generation.

$$0 = g - hR - 2hq_i - hq_j - hR_i - C_i'(q_i) \tag{2}$$

for $i, j = 1, 2$ and $j \neq i$. Let (q_1^*, q_2^*) be the pair of equilibrium thermal outputs and let $p^* = g - hR - hq_1^* - hq_2^*$ be the equilibrium market price. The equilibrium price and quantities depend on vector $\overline{R}$ of renewable energy. The following two propositions characterize how changes in renewable energy for strategic and fringe firms change the equilibrium price. Both propositions assume that there is positive thermal output for strategic and fringe firms. If thermal outputs are zero and renewable output is on the margin, then the impact of additional renewable output on price is the same regardless of renewable ownership.

Proposition 1 *The following results hold in equilibrium*:

(i) *An increase in renewable energy owned by competitive fringe firms has a larger price-reducing effect than an identical increase in renewable energy owned by a strategic firm. That is,* $\frac{dp^*}{dR_f} < \frac{dp^*}{dR_i} \leq 0$ *for* $i = 1, 2$.

(ii) *If marginal cost is constant for a strategic firm, then an increase in renewable energy by that firm has no effect on equilibrium price. That is,* $C_i''(q_i^*) = 0$ *implies that* $\frac{dp^*}{dR_i} = 0$.

Proofs are in the Appendix. A marginal increase in renewable energy owned by fringe firms reduces the equilibrium price and increases total energy output. Acemoglu, et al (2017) refer to this as the merit-order effect, in which an increase in the supply of zero-marginal-cost renewable energy by fringe firms reduces residual demand for strategic firms and lowers the market price. When there is an increase in renewable energy owned by a strategic firm, that firm partially internalizes the price-reduction effect by reducing its thermal output by a larger amount than when the additional renewable energy is owned by fringe firms. Part (ii) of the Proposition illustrates an extreme case of this internalization. If the strategic firm's marginal cost is (locally) constant, then that firm offsets an increase in renewable energy by an equal reduction in its thermal output, leaving the market price unchanged. These results mirror Theorem 1 in Acemoglu, et al (2017), while allowing for asymmetric strategic firms.

Proposition 2 *Suppose marginal cost rises more steeply for firm i than for firm j at equilibrium outputs. Then an increase in renewable energy for firm i has a larger price-reducing effect than an increase in renewable energy for firm j. That is, $C_i''(q_i^*) > C_j''(q_j^*) \geq 0$ implies that $\frac{dp^*}{dR_i} < \frac{dp^*}{dR_j} \leq 0$.*

An increase in renewable energy for a strategic firm reduces the firm's marginal profit associated with thermal energy output and causes the firm to reduce its thermal energy output. The size of the equilibrium reduction of thermal output depends on the steepness of the firm's marginal cost function. If marginal cost of thermal output is very steep, then a firm can restore marginal profit to zero with a relatively small reduction in thermal output, compared to the response of a firm with a flatter marginal cost.[8]

We offer several comments about Proposition 2. First, demand and renewable energy generation may vary substantially both inter-day and intra-day. Given heterogeneity of thermal cost functions, a strategic firm may operate on a steeper portion of its marginal cost than its rival for some hours, and on a less steep portion for other hours. The relative impact on prices of adding renewable capacity for different strategic firms would then depend on the average of these different hourly price impacts. Second, while Proposition 2 refers specifically to local marginal cost conditions, it suggests how capacity and firm-size differences would contribute to different renewable energy price-effects. The marginal cost curve for a strategic firm with multiple thermal generators typically has a hockey-stick shape, with a relatively flat section at low output levels, and progressively steeper sections as output nears total capacity. A large firm with high thermal capacity will tend to operate with a higher markup of price over marginal cost, and therefore operate on the flatter part of its marginal cost curve more often than a smaller rival. Proposition 2 suggests that renewable energy additions by a large strategic firm would tend to have a smaller price-reducing effect than renewable energy additions by a smaller rival. Third, an unambiguous ranking of price effects may be obtained via stronger assumptions on cost functions. For example if costs have the quadratic form, $C_i(q_i) = c_i q_i^2$, then $c_i > c_j \geq 0$ implies $\frac{dp^*}{dR_i} < \frac{dp^*}{dR_j} \leq 0$, for any positive equilibrium thermal energy output levels.

The ownership of new renewable capacity will affect emissions as well as prices. Differing amounts of thermal energy output will be displaced by renewable energy, depending on the ownership of

[8]Proposition 2 uses the assumption of linear demand and fringe supply. If we allow a general demand and fringe supply functions, then a ranking of price effects of renewable energy additions depends on the curvature of inverse demand and relative equilibrium thermal outputs of firms one and two, as well as relative steepness of marginal cost curves.

renewable capacity, and this will lead to differing emissions reductions. Proposition 1 states that strategic firms reduce thermal energy output more than smaller, non-strategic firms in response to a renewable energy increase, so we would expect greater emissions reductions when a large, strategic firm adds renewable energy. Such a result would be consistent with empirical evidence reported by Mansur (2007). He examines how emissions from different types of firms in the Pennsylvania, New Jersey, and Maryland Interconnection (PJM) was affected by the 1999 restructuring. He finds that strategic firms reduced their emissions by approximately 20% relative to other firms and their own historical emissions after restructuring. However we should note that the impact of greater renewable energy on emissions depends not only on how much thermal generation is displaced, but also by what types of thermal generation are displaced. In the next section, we apply our modeling setup to the Ontario wholesale electricity market to explore the effects of ownership of new renewable energy capacity on market prices and emissions.

3 Application to the Ontario Electricity Market

In this section we aim to quantify the impact of renewable capacity ownership on market performance. We study the Ontario wholesale electricity market and examine several wind ownership scenarios to show how different firm ownerships of new wind farms impact the Ontario market prices and emissions. The formulation we analyze in Section 2 is an oligopoly model with two asymmetric Cournot firms facing a competitive fringe. We extend the model for the application to incorporate three strategic Cournot firms and a competitive fringe, in order to capture the structure of the Ontario wholesale electricity market.

We run simulations of the extended model with parameters set to capture conditions in the Ontario wholesale market. The simulation approach is similar to the approach used by Genc and Aydemir (2017). 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, 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.

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. Because the Environment Canada did not update the generation specific data after 2008 and the detailed data is available for the hours of 2007-2008, we employ this data in our simulations.[10] Note that the composition of generation assets in Ontario has gradually changed since 2008 because of Canada's Clean Air Act and most coal-fired generators were shut down as of mid-2015.

[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.

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 SO_2 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				

Following our theoretical model, we use a linear demand function, $D(p) = a - bp$, 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 simulations, 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 hourly as such we pinpoint a linear demand curve passing through the actual market price and quantity for a given level of price elasticity of demand.

We construct and estimate parameters of cost functions for the three strategic firms and fringe supply function for every hour in the study period, following the approach in Genc and Aydemir (2017). First, we construct the total marginal cost of production for the generators characterized in Table 1 using fuel consumption quantity, fuel prices, 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 SO_2 gasses in Ontario[13], the marginal emission costs for a generator is calculated by:

SO_2 marginal emission cost for a generator = Heat rate of generator * SO_2 rate of generator * price of SO_2 emission permit

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

[11]The marginal cost data incorporating fuel consumption, dollars spent and energy content of 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 Genc and Aydemir).

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

The total marginal cost for a generator will then be the summation of marginal fuel cost, SO_2 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. Ontario Power Generation (OPG) has over 60 generators with production technologies of hydro, nuclear, coal, and natural gas. The estimated cost function for OPG 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 $S(p) = a_f + b_fp$. The fringe supply is also capacity constrained, $S(p) \leq K_f$. Note that in our market simulations, the cost coefficients change hourly since we estimate all cost functions 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 changes 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 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). However, this is not a critical assumption: we allow an endogenous import function in the Robustness section and show that market outcomes with exogenous imports are near the ones with endogenous imports. The objective for each strategic firm i is to choose output, $q_{i,t}$, so as to maximize its profit, $\pi_{i,t}$, subject

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

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

Technology	OPG	Bruce Nuc	Brookfield	Fringe_total
Hydro_q (MWh)	3206	-	112	95
Hydro_Kq (MW)	5688	-	662	274
Wind_q	-	-	70	36
Wind_Kq	-	-	189	130
Natural Gas/Oil_q	89	-	48	172
Natural Gas/Oil_Kq	1365	-	59	254
Nuclear_q	4512	3929	-	-
Nuclear_Kq	4539	4040	-	-
Coal_q	3029	-	-	-
Coal_Kq	4034	-	-	-
Biomass_q	-	-	-	129
Biomass_Kq	-	-	-	188
All_Tech_q (MWh)	10836	3929	230	432
All_Tech_Kq (MW)	15626	4040	910	846

Notes: Kq is the available capacity per hour.
Fringe_total refers to total fringe output and capacity.

to production constraints for each hour, where:

$$\pi_{i,t} = p_t(Q_t)q_{i,t} - c_{i,t}(q_{i,t}) \tag{3}$$

and $0 \leq q_{i,t} \leq K_{i,t}$. 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.

Table 2 reports actual output/capacity by firm and technology ownership of the firms in Ontario during the study period. There are roughly 100 small generators owned by small firms and/or entrepreneurs (fringe suppliers). From the table, it is clear that average capacity per fringe firm is less than 10 MW. The three largest firms (OPG, Bruce, and Brookfield) are assumed to have market power, given their market shares and technology mix. With this assumption, Genc and Aydemir (2017) show that simulation outcomes (prices and outputs) are very close to observed outcomes.

In calculating the quantity of emissions, we use each generator's NOx and SO_2 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,

Table 3: Summary Statistics - Actual versus Model Outcomes

	Actual Market	Model Prediction
Demand/Supply 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
SO_2	25968	11208
CO_2	7942254	5515073
n (hours)	2184	2184

landfill gas, coal (lignite, bituminous, sub-bituminous), natural gas, oil. Among those technologies, coal (lignite, bituminous, sub-bituminous) plants are the main source of SO_2 emissions.[15] As the CO_2 rates of Ontario generators 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 CO_2 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 SO_2 rates recorded. The SO_2 rates of natural gas plants are zero in the dataset.

4 Performance of the Ontario Market Model

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

[15]According to the Environment Canada (2004) Canadian Module Unit List, SO_2 rates of all natural-gas fired plants in Ontario are zero.

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 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 supply and the total emissions. Normally, at a negative price the Cournot model should predict zero supply quantity. At the negative minimum price of -1.01, predicted by the model, the strategic 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 addition, fringe sector in our model could also supply a positive output at a negative price, as the estimated fringe supply curve would pass through the second quadrant for some hours. This is congruent with actual behavior in electricity markets in which some wind and solar generators supply power at the negative market price. This is because their price is subsidized at a fixed rate irrespective of market price.

Predicted emissions from the model are lower than actual emissions. There are several possible reasons. One contributing factor is that average predicted output is slightly less than average actual output. Also, the model assigns output and emissions to a firm's plants using the merit order up to total predicted output for the firm. Actual outputs and emissions may differ from this assignment for at least two reasons: i) we do not consider network constraints which can impact the assignment of generation to plants; ii) we do not consider unit start-up costs (which may influence dispatch) or constraints such as ramp-up and ramp-down limits.[17]

5 Results for Wind Ownership Counterfactuals

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 low 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

[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. The PATH solver is used for similar problems in Genc (2003) and Bushnell, et al (2008).

[17] As pointed out by a referee, our estimated cost functions might be biased without consideration of ramp-up/down and start-up costs.

as a study period during which wind generation levels and 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 hypothesized 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 in which OPG would own and run the new wind farms. This scenario has not been materialized in the following years contrary to the directives of the Green Energy Act of Ontario, which allowed OPG (the largest producer, which is a Crown Corporation) to add renewable generation assets to its power plant fleet. However, this is still a likely and interesting scenario for the future because Ontario has been aiming at increasing its green energy production portfolio over the years. These simulations 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

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

consider realizations of 600 MW and 1200 MW new wind capacity additions, respectively, into the market. To compute hourly wind outputs associated with the new capacity expansion, we multiply the hourly wind capacity utilization rates (i.e., capacity factors) with the new capacity. The impact of these new investments on wind output distribution is presented in Table 4. As in the model section, all wind energy is assumed to be supplied to the market in the simulation exercises (i.e., no wind curtailment).

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 equilibrium outputs, prices and emissions are reported. We add extra wind output stemming from the wind investment 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 outputs. We distribute each firm's aggregate output over its generators in merit order (the least costly manner) and then calculate NOx, SO_2 and CO_2 amounts (in tons) 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 market structure as of 2007 is represented by $\omega = K$, referring to model simulation using available production capacities and technologies at that time.

In Table 5, we do not report any emissions for Bruce Nuclear, because it does not emit any NOx,

SO_2 or CO_2 according to Environment Canada. Technically nuclear plants may release some carbon dioxide; because its rate is very small all researchers, to our knowledge, neglect nuclear plants' CO_2 emissions. Also, for all wind generation scenarios the amount of SO_2 released by Brookfield and fringe suppliers are zero because their generators' SO_2 rates are zero according to Environment Canada, as listed in Table 1. As expected, in Table 5, the equilibrium NOx and SO_2 emissions (in ton) are very low relative to the amount of CO_2 emissions.

Observe that the difference between demand quantity (Q_{Demand}) and the total production of all firms (q_{OPG} plus q_{Bruce} plus q_{Brook} plus q_{Fringe}) is due to the imports, which also vary depending on the amount of wind generation. 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 \$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 sizable.

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

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	9404.9	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	39
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

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 increase output by 200 MWh. These results are due to OPG's market power and Brookfield's high share of renewables.

Increased wind generation yields lower emissions in both ownership scenarios. The total CO_2 in Fall decreases about 2.42% under Brookfield ownership and about 4.23% 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 200 MWh (that is from $\Delta\omega = 2K$ to $\Delta\omega = 4K$), aggregate CO_2 emissions drop by 2.45% under Brookfield ownership and about 2.99% under OPG ownership. With new wind farm production OPG displaces output from coal and/or gas plants. On the other hand, with new wind production Brookfield displaces a small amount gas-fired generation. This is because Brookfield's market share is relatively small (therefore, increases its total output at the rate of new wind production). Consequently, under OPG's wind ownership the electricity market produces lower greenhouse gas emissions. In terms of NOx and SO_2 emissions, the environmentally congenial solution is again the OPG's ownership of new wind farms. These results on ownership effects on emissions are analogous to results reported by Mansur (2007). Following wholesale electricity market restructuring, Mansur finds that strategic firms reduced their emissions by approximately 20% relative to other firms and their own historic emissions.

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 CO_2 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 SO_2 emissions, 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 CO_2, NOx, and SO_2.

The results predicted by our simulation exercises are consistent with our theoretical predictions examining the impact of strategic firms' wind generation ownership (OPG versus Brookfield). Proposition 2 shows that the strategic firm with steeper marginal cost at equilibrium output has a larger price-reducing effect than the other strategic firm as a response to an increase of equal amount of renewable energy. In simulations we find that Brookfield reduces prices more than OPG does. From the data (Tables 1 and 2) we know that OPG has over 60 plants/generators mostly with large nuclear and hydro units which form the base-load (or "off-peak") generators. The "mid-peak" plants are its coal-fired units, and gas/oil fired units form its "on-peak" stations. At equilibrium outputs, OPG uses its off-peak and mid-peak generators for most of the hours. On the other hand, Brookfield uses its natural gas-fired generators mainly during peak hours. This suggests that on average Brookfield's marginal cost is higher than OPG's cost at equilibrium outputs. Therefore, an increase in wind energy for Brookfield should have a larger price-reducing effect than an increase in wind generation for OPG. Furthermore, Proposition 2 suggests that renewable energy additions by a large strategic firm would tend to have a smaller price-reducing effect than renewable energy additions by a smaller rival (see the comments about Proposition 2 on page 7). From Table 2 it is also clear that OPG is the largest firm in the Ontario market meeting more than 60% of market demand and Brookfield is a smaller rival. Consequently, our simulation results support the theoretical predictions of Proposition 2.

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 SO_2, NOx and CO_2. 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.

6 Robustness

In the previous sections, we assumed that imports are exogenous because imports are scheduled ahead of time and other suppliers observe the scheduled import quantities. However, importers might base their trade decisions on some price information. Therefore, this opens up the question of what happens if imports are endogenous. Consequently, we assume a linear import function, which takes the form of $I_t(p_t) = a_I + b_I p_t$. Using historical prices and import quantities we run a regression and obtain estimates of the coefficients. We then use this import function in the residual demand function of the strategic firms assuming that importers are price takers. Therefore, in our simulations fringe firms and importers are non-strategic, as there are many of them and each one is very small compared to the size of the market. Given this endogenous import function we run the model and compare the results to the case with exogenous imports when wind outputs are at their actual levels. We calibrate the model in March 2008, the last month of the study period, for 744 hours. The descriptive statistics of equilibrium outcomes along with firm level emissions are tabulated below.

In Table 6 market demand equals total production by the firms plus imports. We observe from this table that market outcomes (market prices, firm outputs, aggregate consumption, and emissions) under exogenous imports ($I(p) = \overline{I}$, that is imports equal to their actual levels) are similar to outcomes with endogenous imports ($I(p) = a_I + b_I p$, that is imports are based on market prices). An endogenous, price-sensitive import supply function yields more price-responsive residual demand functions for strategic firms, resulting in less exercise of market power and (slightly) lower prices on average. The largest strategic firm, OPG, produces more output and has higher emissions in the endogenous imports formulation. However, we note that these effects are relatively small. Consequently, we conclude that our findings reported in the Section 5 under various wind generation ownership scenarios are robust to the choice of import function (whether it is constant or price dependent). This finding springs from the fact that imports are non-strategic and small relative to the size of the market.

Next, as a further robustness check, we perturb the price elasticity of demand to examine the sensitivity of model results to the choice of elasticity assumption. Throughout the analyses we have chosen elasticity as 0.6 which was optimized to fit the actual data along with Cournot firms with

Table 6: Exogenous versus Endogenous Imports

	$I(p) = \overline{I}$	$I(p) = a_I + b_I p$
Wind	$\omega = K$	$\omega = K$
Quantities_mean (MWh):		
Q_{Demand}	19477	19531
q_{OPG}	11228.2	11279.2
q_{Bruce}	3626	3627
q_{Brook}	467.7	468.1
q_{Fringe}	2083.2	2078.8
Price (\$/MWh):		
mean(p)	58.65	58.32
st.dev.(p)	22.95	22.51
skew.(p)	1.81	1.67
kurt.(p)	4.49	3.76
Emissions by Firm (ton):		
Total *OPG* Emissions		
NO_x	888	936
SO_2	3136	3273
CO_2	1162280	1197780
Total *Brook* Emissions		
NO_x	28	28
SO_2	0	0
CO_2	25674	25674
Total *Fringe* Emissions		
NO_x	704	701
SO_2	0	0
CO_2	704510	702543
Total Emissions (ton)		
NO_x	1620	1665
SO_2	3136	3273
CO_2	1892464	1925997
n (hours)	744	744

fringe competition framework. While this elasticity figure is in bounds of what is reported in the literature, it may seem a bit high in the short-run. However, in a Cournot model one has to assume an elasticity figure which is at the higher end of elasticity estimates so as to replicate the actual data. This is a well-known drawback of applying a Cournot model to analyze wholesale electricity markets. Alternatively, one could increase the number of strategic firms along with a small elasticity figure to come up with model outcomes near the actual ones. However, this would need a justification for a power market other than the Ontario one, as there are only a few strategic producers in Ontario as mentioned in the modeling section. After perturbing the elasticity by plus 0.05 and by minus 0.05, we obtain the demand function coefficients for each hour using the actual price and quantity data. We then run the model for each elasticity number and find that the model outcomes do not deviate much from the actual outcomes (we obtain a low mean square error).[18] This finding confirms that one could choose an alternative elasticity figure in the neighborhood of 0.6 for the Ontario market calibrations to assess the value of renewable energy penetration.

7 Ex-post Empirical Evidence

Our simulations were based on generator-specific detailed data from 2007-08 when wind generation was an insignificant part of the generation portfolio of the Ontario market. Over the years since then, strategic and fringe firms have accumulated substantial wind generation capacity. To provide empirical evidence for model predictions and further assess and quantify the ownership impact of wind generation after these capacity investments, we utilize recent generator and market level data covering all hours of 2014. We obtain the hourly production data from the IESO and aggregate greenhouse gas (GHG) emissions data from Environment and Climate Change Canada for all generators in Ontario.[19] The greenhouse gasses include CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, and are reported in tons CO_2 equivalent.

We first map generators to firms to pinpoint the generation assets of each firm. We observe that the Ontario market structure has changed significantly from 2007 to 2014, with more renewables and less carbon-emitting generators including coal-fired plant decommissioning. To be specific,

[18] The results are available from the authors upon request.

[19] The emissions data for electricity sector, with NAICS code 2211, is available at http://www.ec.gc.ca/ges-ghg/donnees-data/index.cfm?do=results&lang=en&year=2015&gas=all&facname=&prov=ON&city=&naics=2211&submit=Submit

Table 7: Summary Statistics for Hourly 2014 Ontario Data

	Average	Minimum	Maximum
Price (Can$/MWh)	32.39	-110.10	964.28
Load (MWh)	18,067	12,741	25,980
GHG emissions (tons CO_2 equivalent)	760	138	4808
Total Wind (MWh)	774	16	2,690
Brookfield Wind (MWh)	119	1	389
Fringe Firms' Wind (MWh)	655	12	2,371

as percentages of total output, nuclear generation represented 52% in 2007 whilst 62% in 2014, hydroelectric generation totaled 21% in 2007 but 24% in 2017, coal-fired generation was at 18% in 2007 versus less than 1% in 2014. While other fuel types (natural gas, oil, wind, biomass, solar etc.) totaled 9% in 2007, they were at 14% in 2014 (with 4% share of wind).[20] Notably, the aggregate wind output in 2014 was almost 7 times higher than in 2007: 6.7 TWh in 2014 versus 1 TWh in 2007.

Summary statistics for 2014 hourly wholesale prices, loads, GHG emissions, and wind generation are reported in Table 7. Most of the wind generation comes from fringe suppliers followed by the strategic firm, Brookfield. Brookfield also operates hydro turbines and natural gas generators. Interestingly, the dominant producer OPG has only installed 2 MW of wind turbine capacity (by 2017). Hourly GHG emissions are computed by using data on 2014 annual total emissions for all fossil fuel-fired generators coupled with actual hourly generation for each generator. We calculate a GHG emissions rate (tons CO_2 equivalent per MWh) by dividing total emissions of a generator by its total generation. Next we multiply this generator-specific emissions rate by actual hourly generation of the generator for each hour of 2014. Then we add all generators' emissions for a given hour to form the hourly total emissions data.

7.1 Impact of Ownership on Prices

We run OLS regressions to quantify the impact of wind generation ownership on wholesale prices (HOEP-hourly Ontario energy prices), which was the main theme of the propositions in Section 2.

[20]Sources are http://www.ieso.ca/corporate-ieso/media/year-end-data/2007 and http://www.ieso.ca/corporate-ieso/media/year-end-data/2014

Our goal is to assess whether or not wind generation from strategic firms affects wholesale market prices differently than wind generation from non-strategic fringe firms. OPG, the largest strategic firm, owns virtually no wind capacity, so we focus on the effect of wind generation from strategic firm Brookfield versus the effect of wind generation from fringe firms.

Identifying separate effects of Brookfield wind and fringe firms' wind on prices is potentially challenging. Hourly generation from Brookfield wind turbines and fringe firms' wind turbines are highly correlated. Incorporating both Brookfield wind output and fringe firms' wind output as regressors in a single regression presents a multicollinearity issue and may yield unreliable coefficient estimates. Running separate regressions that exclude either Brookfield wind or fringe firms' wind may yield coefficient estimates that are subject to omitted variable bias. In order to address these potential difficulties we adopt a specification that includes total wind generation and strategic firm (Brookfield) share of wind generation as regressors. Including the share regressor permits us to identify the wind ownership effect while avoiding multi-collinearity and omitted variables issues.

We consider two main regression specifications. The first specification is a regression of wholesale price P_t on load L_t and total wind generation W_t^{Total}. The second adds Brookfield's share of wind generation S_t^{Brook} as a regressor.

$$P_t = \theta_0 + \theta_1 L_t + \theta_2 W_t^{Total} + \epsilon_t, \tag{4}$$

$$P_t = \delta_0 + \delta_1 L_t + \delta_2 W_t^{Total} + \delta_3 S_t^{Brook} + \epsilon_t, \tag{5}$$

Results are reported in Table 8. Models P1 and P2 use specifications (4) and (5), respectively. Models P3 and P4 add hour-of-day dummy regressors to P1 and P2. Estimated coefficients for load and total wind generation are similar across the 4 models. An additional MWh of load raises wholesale price by 1 - 1.5 cents, while an additional MWh of wind generation reduces wholesale price by about 1.5 cents. The estimated share coefficient (δ_3) is positive and significant for the models with and without hour-of-day dummies. This implies that the price-reducing effect of wind generation is larger for fringe firms' wind than for the strategic firm's (i.e., Brookfield) wind.[21] This empirical result is consistent with part (i) of Proposition 1. This result is also broadly consistent

[21]This result may be seen by comparing the derivatives of price with respect to fringe firms' wind and Brookfield wind: $\partial P_t/\partial W_t^{Fringe} = \delta_2 - \delta_3 S_t^{Brook}/W_t^{Total} < \partial P_t/\partial W_t^{Brook} = \delta_2 - \delta_3 S_t^{Brook}/W_t^{Total} + \delta_3/W_t^{Total}$

Table 8: OLS Regressions - Impact of wind generation ownership on prices

	Model P1	Model P2	Model P3	Model P4
$const.$	-156.68*	-163.40*	-192.60*	-198.10*
	(3.725)	(3.776)	(4.792)	(4.811)
L	0.011*	0.011*	0.014*	0.014*
	(0.0002)	(0.0002)	(0.0003)	(0.0003)
W^{Total}	-0.015*	-0.014*	-0.016*	-0.015*
	(0.0007)	(0.0007)	(0.0007)	(0.0007)
S^{Brook}		42.42*		39.89*
		(4.549)		(4.487)
Hour Dummies	No	No	Yes	Yes
F	1455	1008	132	131
R^2	0.249	0.257	0.272	0.279
$n\,(hours)$	8760	8760	8760	8760

Note: $*$ indicates $p < 0.01$

with the simulation results of Section 5 on wind ownership effects. There we found that allocating new wind capacity to a large strategic firm has a smaller price-reducing effect than allocating new wind capacity to a smaller firm.

7.2 Impact of Ownership on GHG Emissions

Next we examine the impact of wind ownership on GHG emissions, using 2014 market data. Mirroring our analysis of price impacts, we consider the following two regression specifications:

$$GHG_t = a_0 + a_1 L_t + a_2 W_t^{Total} + \epsilon_t, \tag{6}$$

$$GHG_t = b_0 + b_1 L_t + b_2 W_t^{Total} + b_3 S_t^{Brook} + \epsilon_t, \tag{7}$$

Estimation results are reported in Table 9. Models E1 and E2 use specifications (6) and (7), respectively. Models E3 and E4 add hour-of-day dummy regressors to E1 and E2. The coefficients of load and total wind output variables are significant at the one percent level for all models. Estimation results indicate that a 1 MWh increase in load adds about 0.2 tons of GHG emissions. On the other hand, a 1 MWh increase in total wind output reduces GHG emissions about 0.18 tons.[22] The

[22]The estimated emission reductions associated with wind output are similar to prior estimates for the Ontario system, reported in Genc and Aydemir (2017). Novan (2015) reports a much larger emissions reducing effect of wind output, using data from the Electric Reliability Council of Texas (ERCOT). The generation portfolio in Ontario has relatively more hydro and less fossil fuel generation compared to a system such as ERCOT.

Table 9: OLS Regressions - Impact of wind generation ownership on GHG emissions

	Model E1	Model E2	Model E3	Model E4
$const.$	-2697*	-2765*	-3376*	-3429*
	(30.499)	(30.837)	(37.31)	(37.37)
L	0.199*	0.198*	0.243*	0.242*
	(0.0017)	(0.0017)	(0.0020)	(0.0020)
$W^{\boldsymbol{T}otal}$	-0.179*	-0.170*	-0.202*	-0.193*
	(0.0061)	(0.0061)	(0.0058)	(0.0058)
S^{Brook}		429.17*		384.90*
		(37.149)		(34.850)
Hour Dummies	No	No	Yes	Yes
F	6810	4653	672	659
R^2	0.609	0.615	0.657	0.662
$n\,(hours)$	8760	8760	8760	8760

Note: $*$ indicates $p < 0.01$

magnitudes of estimated load and wind effects are slightly larger for the models with hour-of-day dummies.

The predicted effect of wind ownership on emissions reductions from wind output is ambiguous, as this effect depends on both the amount of alternative generation displaced by wind output and on the emissions rates of displaced generation. The positive coefficient for Brookfield's share of wind output implies that wind output from Brookfield has a smaller emission-reducing effect than wind output from fringe firms. This is not necessarily the result we would expect, given our theoretical results on price and output effects of wind output changes and the empirical results on price-effects of wind output changes reported in the previous sub-section. If emissions rates for displaced generation are roughly the same for Brookfield wind and fringe firms' wind then we would expect Brookfield wind to have a larger emission-reducing effect than wind output from fringe firms. A possible explanation for our estimated wind ownership impact on emissions-reductions lies in the nature of Brookfield's generation portfolio. In 2014 Brookfield's non-wind generation capacity was about 90% hydro and 10% natural gas turbine.[23] When wind output increases we expect some reduction in output from non-wind generators, ceteris paribus. If Brookfield responds strategically to increases in wind generation, then it is likely to reduce its own non-wind generation - which is predominantly hydro - more in response to an increase in own-wind, compared to its response to an increase in fringe

[23]The source is www.ieso.ca

firms' wind. The overall output response to a wind increase depends on the combined responses of all suppliers in the market. Brookfield's strategic response to more wind output, coupled with output reductions from other firms, could yield the kind of wind ownership effect on emissions that we find in Table 9.

8 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 investment/production as wind and solar generators are technologies with zero marginal operating cost. 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. Market outcomes under ownership of wind farms by a large strategic firm (OPG) are different than those under ownership by a smaller strategic firm (Brookfield). Emissions and market prices are found to decrease nonlinearly in wind generation. Emissions reductions due to wind are affected by who operates wind turbines, as well as by wind utilization rates (i.e., capacity factors).

A policy implication of our results is that regulators and policy makers should consider carefully how green certificates (i.e., the rights to operate green technologies) are allocated. Based on our simulation analysis of the Ontario market as of 2007-2008, as well as our empirical analysis of the Ontario market as of 2014, we find that wholesale electricity buyers benefit when a smaller firm operates new wind farms rather than a larger firm, because market prices are lower under smaller firm ownership. Wind ownership also matters for emissions, although the mechanism is more complex as it depends on both changes in outputs of generators in response to wind changes and on emissions rates of generators. In our counterfactual analysis of the Ontario market as of 2007-2008 we found that allocating additional new wind capacity to the largest strategic firm (OPG) resulted in substantially lower emissions than allocating additional new wind capacity to a smaller strategic firm (Brookfield). In our empirical analysis of the Ontario market using 2014 data, we found that additional wind generated by wind turbines owned by small fringe firms resulted in lower overall emissions than additional wind generated by wind turbines owned by a larger strategic firm (Brookfield). This result appears to be driven by Brookfield's relatively low-emissions generation portfolio.

9 Appendix

Proofs of Propositions 1 and 2

Equilibrium outputs (q_1^*, q_2^*) satisfy the pair of equilibrium conditions (2). We define $\omega_i \equiv C_i''(q_i^*)$ in order to simplify notation below. By totally differentiating (2) with respect to equilibrium outputs and the elements of $\overline{R}$ we derive:

$$\begin{bmatrix} 2h + \omega_1 & h \\ h & 2h + \omega_2 \end{bmatrix} \begin{bmatrix} dq_1^* \\ dq_2^* \end{bmatrix} = \begin{bmatrix} -h(dR_f + 2dR_1 + dR_2) \\ -h(dR_f + dR_1 + 2dR_2) \end{bmatrix} \tag{8}$$

Let $\psi \equiv (2h + \omega_1)(2h + \omega_2) - h^2 > 0$. Now we can use equation (8) to derive the effects of changes in renewable energy on q_i^* for $i, j = 1, 2$ and $j \neq i$:

$$\frac{dq_i^*}{dR_f} = -h(h + \omega_j)/\psi < 0 \tag{9}$$

$$\frac{dq_i^*}{dR_i} = -h(3h + 2\omega_j)/\psi < 0 \tag{10}$$

$$\frac{dq_i^*}{dR_j} = -h\omega_j/\psi \leq 0 \tag{11}$$

Equilibrium price is, $p^* = g - hR - hq_1^* - hq_2^*$. We use the definition of equilibrium price coupled with equations (9) - (11) to derive the following effects of renewable energy changes on equilibrium price, for $i = 1, 2$.

$$\frac{dp^*}{dR_f} = -h(h + \omega_1)(h + \omega_2)/\psi < 0 \tag{12}$$

$$\frac{dp*}{dR_i} = -h\omega_i(h + \omega_j)/\psi \leq 0 \tag{13}$$

Propositions 1 and 2 follow from the pricing results in (12) and (13).

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