Electricity Trade Patterns in a Network

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Abstract: Using high frequency trade volume and price data in a transmission network we investigate patterns of trade and its impacts in the market price formation process. In particular, we study the Ontario wholesale electricity market and its trade with multiple interconnected markets, including New York, Michigan, and Minnesota, through 13 interconnections. This research has regulatory implications on integration of electricity markets, and possible investments in transmission and production capacity. The main findings are in order: a) imports are unambiguously related to prices (significant Granger causality), while exports are not; b) trade mainly occurs due to the market price differentials between the markets and traders can use past price observation to take trade positions before the markets clear; c) there is a high degree of integration across the markets in the network, where the speed of convergence of cross prices is almost instantaneous.

Keywords: electricity trade; transmission network; electricity prices; event study; non-linear Granger causality; Ontario, New York, Michigan, Manitoba, Quebec wholesale electricity markets.

JEL codes: C10, L94, Q4

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1. Introduction

Electricity market restructuring throughout the world has led to significant evolutions, especially in the production and transmission sides of the industry. Competitive market designs, efficient auction institutions, and welfare improving transactions have radically changed the wholesale electricity markets. Moreover, open access in transmission has led to more electricity flows across interconnected jurisdictions.

One of the aims of electricity market reforms is to increase welfare, notably through trade, and reduce price differentials between states/provinces/countries. Exports and imports, in theory, should minimize price differentials in the absence of network externalities and transmission capacity constraints. However, these constraints always exist in electricity networks. Accordingly, we will examine interconnected markets and investigate the role of electricity trade on the price formation process in an electricity market. In particular, we will study the Ontario wholesale electricity market and its trade through thirteen interconnections with the neighbouring markets. The current electricity industry reforms also aim to decrease air emissions stemming from power productions. Given that the electricity industry is one of the most polluting sectors in the economy in many part of the world, the new reforms include retirement of coal plants and institute green energy sources such as wind and solar based power generators.

Many studies have analyzed several aspects of the restructured electricity markets; however, interregional trades in interconnected electricity markets and their effects on market prices have largely been ignored. This is an important issue, because it can have a significant impact on market price, and therefore on generation and transmission investments, both within a jurisdiction and outside. Furthermore, as electricity market integration between jurisdictions progresses, more trade is expected. Trade effects should be well understood not only for the political economy of the sector but also to foresee investment patterns in production and transmission capacities.

Electricity has been auctioned in wholesale electricity markets in many parts of the world. In electricity auctions (uniform-price or discriminatory) the last accepted energy offer sets the market price (which is paid to all suppliers in uniform-price auctions, and only to the market clearing marginal supplier in discriminatory auctions). As this last accepted offer can come from a local generator or from a wholesaler importing electricity, the market price can be set from outside the home market. For example, in the New York electricity market (run by the New York Independent System Operator, NYISO) and the Midwest electricity market (run by the Midwest Independent System Operator, MISO) exporters and importers can set the market clearing prices in the day-ahead market. The Ontario market (run by the Independent Electricity System Operator, IESO), which does not have a day-ahead market, allows exports and imports to set the pre-dispatch price one hour before the delivery during the pre-dispatch sequence, and these export and import quantities can be scheduled in the real-time. In commodity markets, imports tend to reduce the product price at the home market. A similar argument could be made for electricity markets; that is, imports would lower the wholesale electricity prices by making more energy available, avoiding the need to accept higher energy offers from the suppliers within the home market. Analogously, exports (energy bids from outside buyers) could increase the market prices, as more expensive energy offers have to be accepted to meet the market demand. In this paper, we test these claims in the Ontario market, and find that they do not hold true in general.

Ontario is the largest province of Canada in terms of population and economy, and its wholesale market has some peculiarities. Despite a competitively set hourly energy market price, some generators are unexposed to market prices because they have the equivalent of contract-for-difference with the local electricity planning organization, the Ontario Power Authority. Furthermore, Ontario has important interconnections with large regulated and deregulated neighbouring markets via its transmission grid, leading to important energy transfers. It also has a very volatile market in terms of prices. Ontario has two main physical markets: the real-time energy market and real-time operating market. Contrary to many US electricity markets, it does not have a day-ahead market: market prices are settled every 5 minutes in real-time. Its market price volatility is higher than the ones in neighbouring jurisdictions such as New England (NE), New York (NY) and Pennsylvania-New Jersey-Maryland Interconnection (PJM). These markets have the two-settlement markets, (day-ahead and real-time markets) in which most of the real-time demand are cleared in the day-ahead market. The high volatility in Ontario market is argued to be correlated with the single-settlement nature of the market which is the real-time balancing market.

There are several papers in the literature that examined the Ontario wholesale electricity market. These papers studied production capacity investments (Genc and Sen, 2008), identification of variables explaining peak price (Rueda and Marathe, 2005), the effects of power outages on prices (Melino and Peerbocus, 2008), and the industrial customers' price responsiveness (Choi et al., 2011) in the Ontario market. These studies, among others, have not considered the effects of trade on market prices. An exception is Serletis and Dormaar (2007) who examine whether exports and imports are related to changes in Alberta market prices. Also, in a recent paper Aydemir and Genc (2013) examine a Cournot competition model to indentify impact of electricity trade (mainly imports) on market outcomes and the air emissions. They argue that power trade can reduce the levels of air pollutants such as CO2, NOx, and SO2 stemming from power production.

The current work is different than others in several aspects: i) using an extensive data set (five-minute and hourly data from 2002 to 2009 in a context where imports and exports are made with five different jurisdictions--New York, Michigan, Minnesota, Manitoba and Quebec-- interconnected through 13 trading zones) we implement event study analysis and recently developed non-linear causality tests to determine trade effects on Ontario prices; ii) disaggregating the high frequency price, and export and import data, we study the neighboring markets and their individual impacts on the Ontario' trade. Also, to motivate our empirical methodology we briefly examine two theoretical competition settings and argue why a theoretical framework might offer different predictions (impacts of trade) than the other. Furthermore, our research entails regulatory implications on the integration of electricity markets, and possible investments in transmission capacity.

There has been no electricity trade theory in the literature. We will briefly examine two theoretical models–Cournot and Supply function equilibrium (SFE) analyses, which are commonly used in electricity market analyses– and their trade predictions. We will describe their shortcomings in explaining the effects of imports on prices. Virtually all trade theories (Ricardian, Heckscher-Ohlin, etc.) explain price differentials among autarky markets and trade effects on income distribution and welfare, and predict that goods will flow from low-price markets to high-price markets, and home market prices drop with imports. However, these theories may fall short in explaining the dynamics of trade in electricity markets due to the peculiarities of electricity and the constantly changing supply and demand conditions at each moment. Moreover, trading electricity between jurisdictions is limited by transmission line capacity and is subject to interventions by system operators. Even exports and imports of electricity can occur simultaneously within a trading period, due to hedging purpose and market rule differences between jurisdictions. In the Ontario market, for example, this type of simultaneous trade (import of energy into Ontario and export of energy from Ontario) is called a wheeling-through transaction.

This paper contributes to understanding of trade patterns in a transmission network and the relationship between imports/exports and market prices. Our main findings are as follows. First, we find that while Ontario imports can be unambiguously tied to the hourly Ontario energy prices, exports cannot. Utilizing linear and non-linear tests, we find Granger causality for all lags in the case of imports. Second, with the disaggregated high frequency data we find that trade mainly occurs due to the market price differentials between the markets and traders can use past price observation to take their future trade positions. Third, we observe a high degree of integration across the different markets in the network, where the speed of convergence of cross prices is almost instantaneous.

The paper is structured as follows. Section 2 describes the structure of the Ontario market and its interconnections. Section 3 briefly examines economic theory predictions of trade behaviour and their shortcomings. Section 4 explains the data set, the methodology, and some results. In the fifth section, Ontario's trade patterns with neighbouring jurisdictions in the network are analyzed. Conclusions are presented in Section 6.

2. The Ontario Electricity Market and its Interconnections

This section describes the Ontario wholesale electricity market structure and its interties in the power network over which Ontario continuously trades electricity.

The Ontario wholesale electricity market has some interesting features. It has a diversified generation portfolio with all types of production technologies (fossil-fuel, nuclear, hydropower, wind, solar, and biomass). It is the most price-volatile market in the region, and among the North American power markets, because only Ontario and Alberta markets in Canada employ one settlement market mechanism in which the market price is formed in the real-time.

The Ontario wholesale electricity market consists of the energy market, operating reserve market, and financial transmission rights market. The Independent Electricity System Operator (IESO) issues dispatch instructions to loads and generators and runs a uniform price auction for every five minutes. The Market Clearing Price (MCP) is set by simply ranking all received energy offers (from generators and wholesalers/importers) in increasing price order, until the forecasted demand is satisfied. The last accepted energy offer sets the market price, which is paid to all suppliers (IESO, 2009d). The Hourly Ontario Energy Price (HOEP) is the average of the twelve 5-minute MCP in a specific hour. HOEP is the price paid by non-dispatchable loads. The IESO governs the wholesale market, ensures the reliability of the integrated power system, and forecasts supply requirements and demand (total Ontario market demand is equal to domestic demand plus export demand). Suppliers submit energy offers (quantity-price pairs) to sell electricity and some wholesale buyers submit energy bids to buy electricity. Although demand is inelastic, some large wholesale customers are able to respond to changes in prices by either shifting some of their demand to off-peak periods or participating in the market and bidding how much electricity they plan to buy at various price levels.[1]

The IESO does not have a day-ahead market. Generation dispatch and market clearing prices are set in the real-time energy market only. However, for reliability purpose the IESO employs a Day-Ahead Commitment Process (DACP), created in 2006, to manage day-ahead available energy units and determine approximate import transactions.[2] On the other hand, US neighbouring jurisdictions (Minnesota, Michigan and New York) have two-settlement markets, namely day-ahead and real-time energy markets. Day-ahead market has the dominant share of transactions in the US markets. The two-settlement market structure enables that most of the market demand is cleared a day before market opens and generators have enough time to adjust their operations for the instances of unpredictable events in real-time.

In 2009 the available generation capacity within Ontario was 35,465 MW (IESO, 2009a). This capacity has grown at an average rate of 2% during the period 2002-2009 (Statistics Canada, 2009), while the total available energy (generation and imports, minus exports) has remained at the same level from 2002 to 2009 (about 155 TWh per year).

2.1 Exports, Imports and Price Formation in the Ontario Market

[1] According to IESO 2010 market's program (www.ieso.ca), there are 13 facilities operating as "dispatchable load" in the market, offering 700 MW of potential demand response.

[2] In 2008 the IESO Board approved the implementation of an Enhanced Day-Ahead Commitment Process (EDAC) to deliver some minor changes to the existing Day-Ahead Commitment Process.

The interconnection capacity between Ontario and its neighbours (two regulated Canadian markets: Manitoba and Quebec; and three deregulated US markets: Minnesota, Michigan and New York) is presented in Table 1, in which the export and import capacities are about 6,000 MWh, which would cover almost one third of the average load in Ontario if there were no transmission and/or network constraints. The actual total export/import capacity is not equal to the arithmetic sum of individual capacities, as the constraints bring it down to 4,000 MW (IESO, 2009c). In Table 1, exports (imports) column represents the maximum export (import) quantities from (to) Ontario to (from) the interconnection. For instance, in a given hour Ontario can sell up to 1,925 MWh to NY, or can import at most 1,680 MWh from NY. Except for a 625 MW addition to the Quebec interconnection in July 2009, interconnection capacities remained very stable from 2002 to 2009. Detailed individual transmission line information is published several times a year by the IESO (see IESO, 2009b).

Table 1. Ontario Interconnection Capacity for Exports and Imports, in MW, 2009 (IESO, 2009b)

	Exports	Imports
Manitoba	268	336
Minnesota	140	90
Michigan	2,275	1,675
New York	1,925	1,680
Quebec	1,329	2,210
Total	**5,937**	**5,991**

Ontario generators can sell their power at the real-time MCP or sell it in external markets. A home generator can export directly to other markets without participating in the home market. That is, it can submit energy offers in other markets before offering its energy to the Ontario market. Therefore, an Ontario generator can export while having no sales in Ontario. However, the system operator may cancel or curtail already scheduled exports for system adequacy or reliability reasons. Importers of electric power are given a price guarantee for their accepted energy offers. If the MCP is lower than the pre-dispatch price of the importer, the difference is paid to the importer by the operator. To signal market conditions, the IESO releases pre-dispatch schedules with forecasted demand and supply requirements (e.g., generation availability, imports and exports) along with the price signals (e.g., projected HOEP for the day, and the intertie offer guarantee estimate). Importers use these market signals before placing their bids. Due to unexpected outages, and/or high start-up costs, and/or high ramping rates of power plants, and/or low spinning reserve capacity, the home market price may increase, which can create a trade opportunity for importers. Depending on the price differentials between the home market and interconnected markets, and on the transmission constraints, importers would benefit from arbitrage opportunities.

Currently, the IESO employs “Dispatch Scheduling and Optimization Algorithm” to determine pre-dispatch sequence of prices and demand for the future periods. These are the predicted prices based on demand and supply forecasts. The algorithm is run every hour, and the pre-dispatch prices and quantities calculated for each hour for the future 12-36 hours are published at the IESO web site[3]. Specifically, market participants can use the pre-dispatch data to reform their operations planning and participation in the real-time market. For example, to increase price responsiveness the IESO can compensate the market participants who could reduce their demand in real-time, if the 3-hour ahead pre-dispatch price were above $120.

Imports and exports are scheduled one-hour before the delivery hour. Imports and exports are settled in the real time at the MCP plus the congestion price, which is determined during the hour-ahead pre-dispatch sequence. Importers are given a price guarantee: if the MCP is lower than their offer price in the hour-ahead pre-dispatch market then they will be paid at least the average price of their pre-dispatched accepted offers. Therefore, pre-dispatch prices are crucial for payments to importers. Pre-dispatch prices also help determine future import offers.

Based on the operations in the hour-ahead dispatch planning and the market clearing in the real-time market, it is comprehensible that imports and exports can potentially affect the real-time prices. Imports offered below the hour-ahead pre-dispatch price and exports bid above the hour-ahead pre-dispatch price are all scheduled in real-time dispatch with sure probability. Therefore, exports and imports will play an important role in determination of real-time market prices. Although, they do not set the market clearing price in real time as they cannot be dispatched in every five minutes, imports and exports can set the pre-dispatch price in the hour-ahead market in Ontario. However, the intertie transactions (exports and imports) can set the day-ahead market prices in the US markets.

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[3] The pre-dispatch prices and quantities are posted at www.theimo.com/imoweb/marketdata/marketToday.asp

It is argued by the IESO Market Pricing Working Group that pre-dispatch prices could approach to the real-time prices if the pre-dispatch prices would be determined five minutes ahead of the real-time auction instead of the hour-ahead operations.[4] The IESO is considering a day-ahead market design which will aim to set electricity prices on an hourly basis one-day ahead of the real-time.[5] In such a day-ahead market design, imports and exports would be able to set the day-ahead market prices. The real-time market, however, will remain effective and run the auction in five-minute basis to clear the unmet demand.

3. Economic Theory Background

To predict the relationship between electricity trade and market prices, we will briefly overview two microeconomic models –Cournot and supply function equilibrium settings– that are commonly used to examine behaviour of power producers and market power issues in the electricity markets.

First consider the following quantity choice Cournot model in which firms choose production quantities as strategies. Let demand for electricity be price responsive, and assume a constant production cost *c*. There are *n* producers and an importer of electricity. For producer *i*, the profit as a function of output is,

$$\pi_i(s_i) = (p(s_i + s_{-i} + I, a) - c)s_i$$

where $p(Q)$ is the inverse demand with the total market output $Q = s_i + s_{-i} + I$, and *I* is the quantity imported, s_i and s_{-i} are the outputs of firm *i* and rival firms –*i*, respectively. The parameter a denotes the demand intercept. Exports are assumed to be part of total market demand, as in the Ontario market; hence we do not need to explicitly take them into account. Assume a concave and downward sloping inverse demand, that is $p' < 0$ and $p'' < 0$, and price increases as the market demand increases, that is $\frac{\partial p}{\partial a} > 0$. Maximization of the above profit function for firm i leads to the reaction function $s_i = -(p - c)/p'$ where $p' = \partial p/\partial Q$. The strategic firm i adjusts its output with respect to the imports as $\frac{ds_i}{dI} = -1 + p''(p -$

[4] See http://www.ieso.ca/imoweb/pubs/consult/mep/MP_WG_2004Aug20_ISS01_PreDispPrice.pdf and the Issue 30 on forecasting real-time prices.

[5] See http://www.ieso.ca/imoweb/pubs/consult/mep/MP_WG-20060303-Issue7-Imports-Exports-Setting-Price.pdf. The day-head market has not been implemented by IESO yet.

$c)/(p')^2$ which is negative since demand is concave. Namely, as imports increase strategic firms tend to decrease their outputs.

If the importer is also strategic it maximizes its profit and responds to rival producers as follows. The profit for the importer is,

$$\pi(I) = (p(s_i + s_{-i} + I, a) - C)I$$

assuming C as the cost per unit for the importer. The importer's profit maximization yields, by the first order necessary conditions, the reaction function $I = -(p - C)/p'$. The importer adjusts its import quantity with respect to the producers' output $s = s_i + s_{-i}$ as $\frac{dI}{ds} = -1 + p''(p - C)/(p')^2 < 0$.

The presence of a strategic importer in this static Cournot model will tend to reduce the market price, as it increases the competition. Furthermore, as the (inverse) demand increases, that is the demand intercept a goes up, the importer imports more: since $p' < 0$ and $\frac{dp}{da} > 0$, we obtain $\frac{dI}{da} = -\frac{\left(\frac{dp}{da}\right)}{p'} > 0$.

On the other hand, if the importer is competitive, that is it is a price taker and supplies up to its capacity at a price level near its marginal cost, it is easy to verify that import quantity will shift the demand curve downwards and hence causes price reduction. Therefore, competitive imports will reduce market price for a given level of demand.

The above analysis is based on a static model in which firms commit to their production and/or import schedules given the other firms' outputs. An alternative model would be utilizing a supply function equilibrium (SFE) model (see, e.g., Genc and Reynolds (2011)) in which each firm chooses price-quantity pairs as strategies. It is richer and more flexible than a Cournot model in the sense that each firm has the ability to choose a supply schedule as a strategy instead of choosing a fixed quantity (Cournot assumption) or a fixed price (Bertrand assumption). In many electricity markets/auctions, including the Ontario wholesale electricity market, firms compete in supply schedules and intersection of a market demand with aggregate supply function determines the market clearing outcome. How much each firm produces ultimately is directed by its own supply function.

To this end, consider the following simple SFE model in which all firms including importer(s) are strategic and market demand varies over time (say, hourly) and is concave. Each electricity producer chooses a supply function $s_i(p)$, specifying the amount the producer is willing to supply at each possible market price that might occur in a trading period. Denote the aggregate supply function of all producers $S(p) = \sum_i s_i(p)$. As a market rule in electricity auctions, a supply function submitted by any producer must be non-decreasing (see Baldick and Hogan (2002), Genc (2010)). This is a reasonable market rule as the bids of a supplier are in merit order, and the rule helps equilibrate the market. All suppliers including importer(s) independently and simultaneously choose supply function strategies to maximize their profits. A supply function equilibrium is a Nash equilibrium in supply function strategies. The supply functions stay constant during the trading period (e.g., a day) in some markets; in other markets suppliers are allowed to submit different supply functions several times a day (e.g., for each hour as in the Ontario market). The intersection of the aggregate supply function and the market demand determines the market price and quantity at the particular time *t*.

The profit function to be maximized at time *t* by the importer is

$$\pi_I(t) = (p(t) - C)\left(Q\big(p(t)\big) - S\big(p(t)\big)\right),$$

in which the residual demand it faces is $I\big(p(t)\big) = Q(p(t)) - S(p(t))$, and the market clearing price is $p(t)$. Assuming that the residual demand function is differentiable, the necessary condition for optimal price choice $p(t)$ for supplying quantity I is the differential equation,

$$I(p) = (p - C)\big(S'(p) - Q'(p)\big).$$

This import function has the characteristic that the importing firm maximizes its profit at each point in time (*t*) during the trading day, given the supply functions chosen by the rival electricity producers.

To see how the imports vary as market prices change, we take the derivative of this expression to obtain,

$$\frac{dI}{dp} = [S'(p) - Q'(p)] + (p - C)[S''(p) - Q''(p)] > 0$$

This expression is positive because the terms in square brackets are positive as the supply functions are non-decreasing and the demand is concave.

Contrasting both Cournot and the SFE model, it becomes clear that under the SFE model increase in market prices will contribute to higher electricity imports. In a static Cournot model this result is not immediate: at a given level of demand imports contribute to price reductions.

The above insights are based on stylized economic models, and our assumptions (symmetry, differentiability, concavity, and non-binding constraints) are too simplistic to be true for real electricity markets. For example, due to the market power issues and the capacity constraints of firms supply functions could be discontinuous (see, Genc and Reynolds (2011)), and the importer could face a non-differentiable residual demand function, which would create an issue to find out the sign of dI/dp, and to characterize and solve an optimal import strategy $I(t)$. Moreover, we ignored dynamic considerations between importers and producers over time and assumed static models to examine the import behaviour. It is a fact in economic theory that dynamic games in general predict different results than static games do. To the best of our knowledge, there is no dynamic SFE analysis in the literature, nor is any SFE analysis incorporating imports and exports in examining optimum bidding behaviour.

4. Econometric Analysis

We show in the theory background section that it could be a daunting task to come up with an electricity trade theory explaining the directions of the imports (and exports) and their influence on the electricity market prices. This is mainly due to the peculiarities associated with the nature of electricity, which makes it different than the other commodities. However, we can apply some time-series econometric methods to investigate the role of imports and exports on market outcomes in the Ontario wholesale electricity market.

Below we explain the data set and the econometric techniques that we employ to study the relationships between trade and market prices. We first begin with an event study analysis, and then employ linear and recently developed non-linear Granger causality tests from export and import volumes to electricity prices.

4.1 Data

Our data set includes the Ontario hourly electricity prices HOEP (P, in Can$/MWh), exports (X, in MWh) and imports (M, in MWh), total market demand (Q, in MWh), and also the five-minute market clearing prices in all neighbouring markets. They span the time period of May 1, 2002 – June 9, 2009 on hourly basis, including all week and weekend days (62,328 data points for each variable)[6]. In addition to the HOEP, we also use 1, 2, 3 hour-ahead pre-dispatch prices[7].

4.2 Event Study

To investigate whether imports or exports are able to affect market prices in Ontario electricity market, we first undertake an event study. Although event study analysis is commonly used in the finance literature, to our knowledge it is the first time this technique is being applied to trade analysis in electricity markets. The purpose of this event study is to analyze the behaviour of prices before and after the "event". Events, in our case, are defined as "high" export or import values. Consistent with the literature, we define the high levels of exports or imports as a level 4 standard deviation above its mean at a certain point in time. In other words, if the total imports (exports) at time *t*, is 4 standard deviation above its mean we call this as an import (export) event[8].

By applying this definition to our entire data set we pin down 208 and 541 events for imports and exports, respectively. The dates of these events are illustrated in Figure 1 along with the market prices. As it can be observed in the figure, almost all of the events are concentrated either before/around 2003 (when the Ontario wholesale market collapsed) or after/around 2008 (when the economic crisis in North America started). Most of the imports events (blue lines) are observed before 2003 or after 2008, which also coincides with some of the export event dates (red lines). The remaining exports events are concentrated near 2003 and 2008 dates in which imports events are not shown up.

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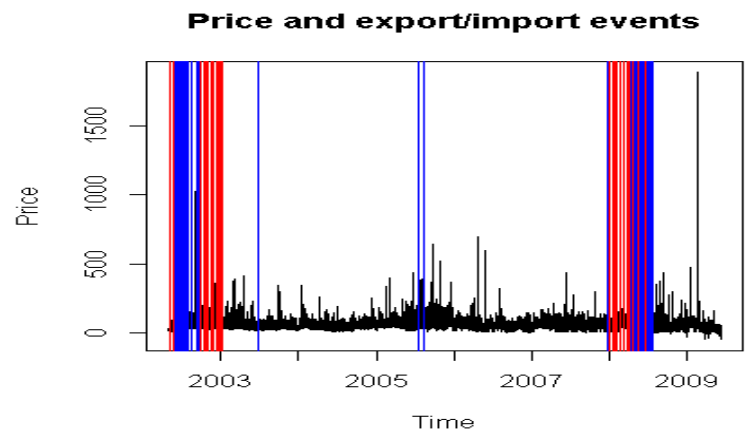
[6] The data is available at www.ieso.ca. We also analyzed this data set in subcategories of peak and off-peak hours and obtained qualitatively similar results. Peak time was defined as hours between 08:00 and 22:00 (including 8.00 and 22:00) during week days and excluding whole weekends (27,825 data points for each variable). Off-peak time data include week day hours between 23:00 -07:00 and whole weekends (34,503 data points for each variable). These results are available upon request.

[7] The pre-dispatch prices were not published by the IESO for August 14-23, 2003 (the period following the Northeast Blackout of 2003).

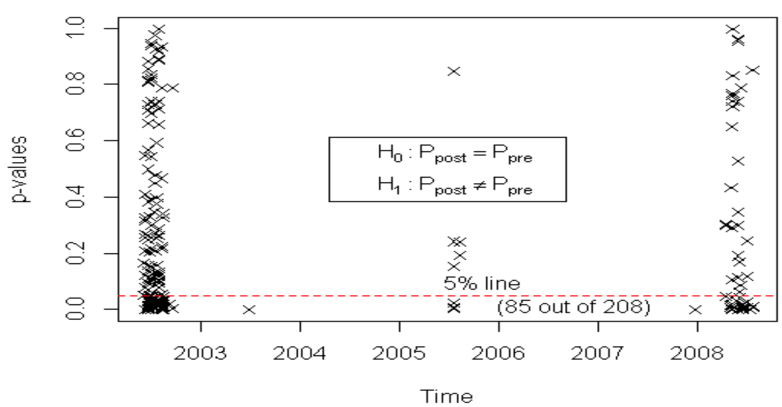
[8] We measure the mean and standard deviation by using the data up to point *t*. We also applied the same event rule by eliminating all prices below the mean, hence we imposed another condition in addition to the above one. This leads to a significant decrease in the number of events; however the results remained qualitatively the same.

Figure 1. Export and Import Events Dates



The next step in our event study is to statistically test whether the electricity prices are affected by these events. To do this we simply test the equality of the mean prices before and after the events by choosing an event window. This window is considered to be the time length in which the effect of the event is supposed to be observed. Then the event window is divided into two halves to test the equality of the mean prices by using the data in the equal parts of the event window. Figure 2 illustrates the results of t-test applied for the null of equal means versus their inequality by using an event window that is equal to 60 points.[9]

Figure 2. Event Study Tests (Imports)

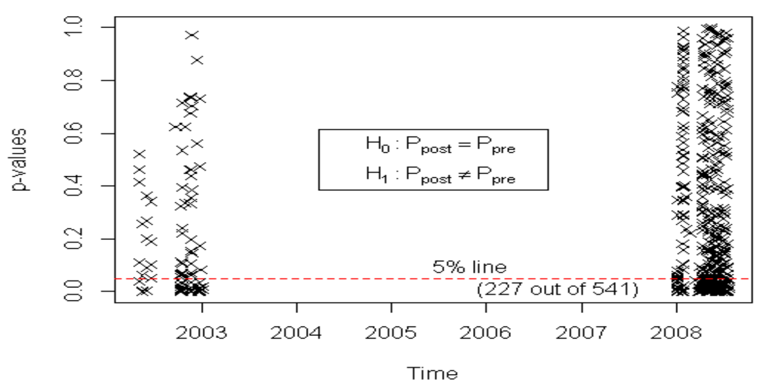


[9] Hence we have 30 data points before and after events to carry out the t-test. We have tried different event windows and obtained qualitatively similar results. They are available upon request. Note also that we assume unequal variances in the t-test.

On the y-axis of the figure we report the p-values of the tests corresponding to each import event points. The points below the 5 per cent line indicate the events for which the t-test resulted in rejection of the null of equality of mean prices at 5 per cent significance level. We obtained 85 of such tests, out of 208 events, in which the import events seem to affect price changes. Hence we conclude that we have sufficient evidence on the influence of imports on price behaviour.

In Figure 3 we repeat the same analysis for export events. We find that in 227 tests, out of 541, the mean prices are significantly different between before and after event periods. This analysis also points out that, like imports, exports have an impact on prices.

Figure 3. Event Study Tests (Exports)



4.3 Testing Granger Causality

During certain export and import events we have found statistically significant evidence of impact of trade activities on the market prices. To gain more insights on the overall trade effects, in particular lingering effects of trade on prices we need to test the Granger-causality from export and import volumes to the market prices. The conventional approach of testing Granger causality is to assume a parametric, linear time series model for the conditional mean and test whether the lags of one variable enter into the equation for another variable. In the linear framework, it is a common practice to test the Granger causality within a Vector Autoregressive (VAR) model using Wald or Augmented Wald test proposed by Toda and

Yamamoto (1995) and Dolado and Luktepohl (1996)[10]. Since the linear test statistics may not be sufficient to detect nonlinear effects on the conditional distribution, their sole usage may lead to spurious causality test results. Therefore, we also perform recently developed nonlinear tests in addition to the conventional linear Granger causality tests.

Serletis and Dormaar (2007) assume four-variable VARs for the Alberta electricity market. Rueda and Marathe (2005) use support-vector-machine-based learning algorithm for sensitivity analysis to detect the main determinants of real-time average peak prices in Ontario. They find that the main explanatory variables of the peak prices are the lagged average peak prices, the actual import peak volumes, the peak Ontario market loads, and the net available supply after accounting for load (excess supply) for the data studied in the period May 2002- May 2003. Due to these reasons we estimate four-variable VARs for the Ontario market. The variables included in VARs consist of electricity prices, export and import volumes and total demand (load)[11]. We test the null hypothesis of Granger non-causality by restricting the relevant coefficients to zero in the following equation of the VAR(p) model.

$$(1) \qquad P_t = \alpha + \beta t + \sum_{i=1}^{p} \phi_{i-1} P_{t-i} + \sum_{i=1}^{p} \varphi_{i-1} X_{t-i} + \sum_{i=1}^{p} \psi_{i-1} M_{t-i} + \sum_{i=1}^{p} \gamma_{i-1} Q_{t-i} + u_t^p$$

where P_t, X_t, M_t, Q_t stand, respectively, for price, export, import and total demand at hour t, and u_t^p represent the usual error term of the price equation of VAR. In this equation, the null of "export does not Granger cause to power prices" and the null of "import does not Granger cause to power prices" are tested by using the following restrictions: $H_0 : \varphi_1 = \varphi_2 .... = \varphi_p = 0$ and $H_0 : \psi_1 = \psi_2 .... = \psi_p = 0$, respectively.

[10] As is well known, in stationary systems the distribution of Wald test is asymptotically chi-squared. However, the asymptotic theory of Wald tests is typically much more complex in systems that involve variables with stochastic trends and the distribution depends on the number of unit roots and cointegration relations in the system (see Toda and Phillips, 1993). The Augmented Wald test is indifferent whether the series in VAR are cointegrated or not, or whether they are I(0) or I(1), or mixed. To avoid pre-testing biases (either in unit root or cointegration tests) one can directly use this procedure without embarking on problematic unit root or cointegration tests. Also note that we tested time series properties of the above variables with different unit root tests and found that they appear to be stationary.

[11] We also included average temperature in Ontario as an additional variable in the system in equation (1). We find that the results outlined here are not sensitive to the presence of average temperature in the system. The results with temperature data are available upon request.

First using the Granger causality tests we will examine whether Ontario market prices are influenced by the exports to the neighbouring jurisdictions. The lag length p in equation (1) is chosen by Akaike Information Criteria (AIC)[12] and both Granger causality tests (augmented and non-augmented) indicate that the null of non-Granger causality cannot be rejected with a p-value of 0.206 (augmented) and 0.193 (non-augmented). Second we examine the impact of imports on the Ontario prices through the Granger causality tests and find that contrary to the exports, the null hypothesis of no causality is rejected from imports to power prices with p-values equal to 0.000. Consequently, we obtain conclusive evidence on causality running from imports to power prices but not for the causality from exports to power prices in linear framework.

In the parametric linear framework, we also repeat the same analysis by using 1, 2, 3 hour-ahead pre-dispatch prices instead of realized spot prices. We obtain the similar results: there is causality from imports to pre-dispatch prices, but not from exports to the pre-dispatch prices.

4.4 A Nonparametric Causality Model

To check the robustness of the results found in the linear model, we run recently developed nonlinear tests. While the parametric approach we employed in Section 4.3 is appealing due to its simplicity, the test statistics are only sensitive to causality in conditional mean and may not be sufficient to detect nonlinear effects on the conditional distribution. Baek and Brock (1992) explain that parametric linear causality tests have low estimation power against certain nonlinear alternatives. For testing causality, nonlinear nonparametric techniques seem to be attractive since they focus on predictions without imposing a certain functional form. Various nonparametric tests have been proposed in the literature. The most commonly used one is developed by Hiemstra and Jones (1994) (HJ, henceforth). HJ test is a modified version of Baek and Brock (1992) test. However, Diks and Panchenko (2005) (DP, hereafter) show that the HJ test is not generally compatible with the Granger causality and leads to the possibility of spurious rejection of the null hypothesis. As an alternative, DP developed a new test statistic that overcomes these limitations. Hence, to test the nonlinear causality between P_t

[12] To determine the lag length chosen by AIC we initially set the maximum p to be equal to 720 (one month). To compute the test statistics we run Matlab codes using Matlab 7.9 64-bit version in an Intel(R) Xeon(R) CPU X5570 @ 2.93GHz and 3.14 GHz, 16 GB of RAM machine. Given the huge matrix operations, the codes would not be able to be run in a less qualified machine due to the large-size data set.

and X_t, and P_t and M_t, we use the DP test. The test is applied to the estimated residual series from the VAR model, u_t^p , u_t^x, u_t^m, where the last two terms refer to the residuals estimated from the export and import equations of the VAR model, similar to the price equation depicted above. By removing linear predictive power, if any, with a linear VAR model, any remaining predictive power of residual series can be considered nonlinear predictive power.

By definition, u_t^x (or u_t^m) strictly Granger causes u_t^p if past and current values of u_t^x contain additional information on future values of u_t^x that is not contained in the past and current u_t^p values alone. More formally, let $\mathbf{u}_t^x = \left(u_t^x, ..., u_{t-l_x-1}^x\right)$ and $\mathbf{u}_t^p = \left(u_t^p, ..., u_{t-l_p-1}^p\right)$, $\left(l_x, l_p \geq 1\right)$ denote the information sets consisting past observations of u_t^x and u_t^p up to and including time *t*. Let "□ " denote equivalence in distribution. Then u_t^x does not Granger cause u_t^p if

(2) $$H_0: \quad u_{t+1}^p \mid \left(\mathbf{u}_t^x, \mathbf{u}_t^p\right) \square \; u_{t+1}^p \mid \mathbf{u}_t^p$$

This is a more general setup for testing Granger non-causality than the above linear case since it does not involve assumptions on the data generation process and the test of noncausility simply consists of comparing one-step-ahead conditional distribution of u_t^p with and without past and current observed values of u_t^x.

The results of DP tests applied to residuals of the linear VARs chosen by AIC is presented in Table 2. As in the previous section the tests are carried out using both actual spot (HOEP) and pre-dispatch prices. The null hypothesis of conditional independence is tested using the lags of VAR residuals in the conditioning set, which is set to 8 as maximum. [13]

The evidence of (nonlinear) non-causality from export volumes to power prices, which also indicated non-causality in the linear case, is highly conclusive for pre-dispatch prices[14]. This evidence of non-causality from exports to prices is also present for market prices, although not as conclusive as pre-dispatch prices. All nonlinear tests cannot reject the null of non-

[13] The C code for computations has been provided by Diks and Panchenko (2005).

[14] We only report the results of 1 hour-ahead pre-dispatch prices. The results with 2 and 3 hour-ahead pre-dispatch prices are qualitatively similar to the results of 1 hour-ahead pre-dispatch prices.

causality at 5 per cent significance level except the one with $l_x = l_p = 8$. On the other hand, the null hypothesis of non-causality from imports to prices is unambiguously rejected in all tests for actual market prices. However, the evidence of causality from imports to pre-dispatch prices differs across the lag lengths considered for the VAR residuals in the DP test. While the non-causality is rejected, as in the case of actual market prices, up to $l_x = l_p = 5$, it cannot be rejected for the remaining lags. Consequently, our results under nonlinear causality tests are in general conformable with the results obtained under the linear counterparts.

Table 2. Nonlinear Causality Tests for different lags with actual market and pre-dispatch prices

	X does not Granger cause P		**M does not Granger cause P**	
$l_x = l_p$	**HOEP**	**Pre-Dispatch**	**HOEP**	**Pre-Dispatch**
1	0.245 (0.403)	-6.362 (1.000)	11.074 (0.000)	3.4915 (0.000)
2	0.399 (0.345)	-8.714 (1.000)	12.451 (0.000)	3.248 (0.000)
3	0.733 (0.232)	-9.579 (1.000)	12.360 (0.000)	2.808 (0.002)
4	0.362 (0.359)	-9.304 (1.000)	10.735 (0.000)	1.879 (0.030)
5	1.073 (0.141)	-9.484 (1.000)	9.601 (0.000)	1.199 (0.115)
6	1.520 (0.064)	-8.983 (1.000)	8.112 (0.000)	1.116 (0.132)
7	1.500 (0.066)	-8.390 (1.000)	7.280 (0.000)	1.103 (0.134)
8	2.455 (0.007)	-8.107 (1.000)	7.010 (0.000)	1.041 (0.148)

Note: T ratios of DP tests are for the bandwidth value of 1.5, the value used by Hiemstra and Jones (1994). P-values are given in the parentheses. l_x,l_p refer to the lags of the variables in the conditioning set.

The results of both linear and nonlinear Granger causality tests indicate that while the evidence for the hypothesis of exports having no causal impact on prices, the evidence for imports is the reverse and points out that imports have an impact on prices. Contrary to the linear case, in the nonlinear DP test the latter result on causality seems to be ambiguous for the pre-dispatch prices.

Despite the evidence on the effect of exports on prices in the event study, we are unable to find evidence on causality running from exports to prices. Notice that the causality tests are carried out by using the whole sample. However, as we see in Section 4.2 that most of the export events are concentrated around/after 2008. Therefore, it is a worthwhile exercise to repeat the causality analysis by using this time period of the data rather than the whole sample. Indeed, by using the data from November 1, 2007 to the final date in our sample we obtain strong evidence on causality from exports to prices for this period where the majority of the export events are present. Both Granger causality tests (augmented and non-augmented) indicate that the null of non-Granger causality can be rejected with a p-value of 0.000 for all prices. The results of nonlinear causality tests for this period, illustrated in Table 3, confirm the results obtained in the linear framework.

Table 3. Nonlinear Causality Tests (1.10.2007-6.9.2009)

	X does not Granger cause to P
$l_x = l_p$	**HOEP**
1	4.468 (0.000)
2	4.407 (0.000)
3	4.038 (0.000)
4	3.352 (0.000)
5	2.385 (0.008)
6	2.221 (0.013)
7	2.380 (0.008)
8	2.343 (0.009)

Although we find the strong evidence on causality from exports to prices for the duration of the financial crisis in the North America, and even study confirms this evidence, an interesting question arises: why exports do not (Granger) cause prices for the entire study period of 2002-2009? In the Ontario market exports are scheduled one hour before the dispatch and performed in the expectation that the market supply is enough to cover Ontario demand. If home market supply security is attained, and the neighbouring markets' expected prices are above the local production cost and/or the home market prices, then the export transactions are carried out. In this case, clearly one does not expect exports to affect the home market prices. On the other hand, the IESO can intervene into export schedules when the home market supply conditions are tight and/or when some home generators fail to deliver the scheduled power. If this case occurs then exports are cancelled out by the system operator, as part of the market rules, to increase the local market supply. Cancelled export schedules become a part of local supply, which should affect the market prices.

In contrast, imports can influence prices in several ways. First, it is clear that the last accepted ask price setting the hour-ahead pre-dispatch price can come from a local generator or a generator from other market via imports. Therefore, the pre-dispatch prices and scheduled imports in the hour-ahead planning can affect the market clearing prices in the real-time uniform-price auction. Second, imports are additional sources of supply, hence can affect supply schedule and the price formation in the market. Therefore, one can expect a significant causal impact (Granger causality) from imports to prices, and the empirical evidence obtained above is in line with this expectation.

In the following section, we examine disaggregated trade data between Ontario and its main trading partners.

5. Trade Patterns between Ontario and the Neighbouring Jurisdictions

Having analysed the impacts of trade on electricity prices we now open the question of why the trade between Ontario and its trading partners takes place in the first place. To address this question we use disaggregated imports and exports data which shows bilateral trade flows between Ontario and others. These data are available for a long horizon in our data set, covering from December 10, 2003 to December 31, 2008 in hourly basis, and we have also a higher frequency data with 5-minute intervals (532,512 observations in total). The data consist of imports and exports of Ontario from and to the 13 interconnections, and the actual market prices in these 14 markets. These markets are Ontario (ONT) Manitoba (Man), ManitobaSK (ManSK), Michigan (MICH), Minnesota (MINN), New York (NY), and eight trading zones in Quebec (denoted by PQ.BD, PQ.DZ, PQ.DA, PQ.HZ, PQ.HA, PQ.PC, PQ.QC, PQ.XY).

The comparison of the prices between Ontario and its 13 trading markets is sketched in Table 4. Second and third columns of the table illustrates the percentages of the observations for which the prices are the same or different in the bilateral markets out of 532,512 observations. For instance for Ontario's trade with Manitoba, while 98.2 per cent of the time electricity prices in Manitoba are exactly the same as those of Ontario, only in 1.8 per cent of the time they are different. In other markets, this ratio of price equivalence is even higher, reaching as high as 99.97 per cent.

This similar pricing behaviour is certainly an interesting future in this north-east transmission network connecting Canadian to the US power markets. It reflects the high degree of market integration across the different markets in different locations. It also indicates that the law of one price (LOP) holds in this network and the speed of convergence of cross prices is almost instantaneous.[15] A detailed examination of these interesting findings is beyond the scope of this paper and could be pursued in a future research.

Table 4: The comparison of the prices between Ontario and its trading partners

	SAME	**DIFFERENT**	**SAME**	
			Trade	**No Trade**
Man-ONT	98.20%	1.80%	0.30%	99.70%
ManSK-ONT	89.43%	10.57%	0.20%	99.80%
MICH-ONT	85.71%	14.29%	1.21%	98.79%
MINN-ONT	87.94%	12.06%	0.20%	99.80%
NY-ONT	99.43%	0.57%	9.45%	90.55%
PQ.BD-ONT	99.94%	0.06%	3.72%	96.28%
PQ.DZ-ONT	99.79%	0.21%	1.77%	98.23%
PQ.DA-ONT	99.98%	0.02%	45.70%	54.30%
PQ.HZ-ONT	92.96%	7.04%	1.04%	98.96%
PQ.HA-ONT	99.84%	0.16%	27.38%	72.62%
PQ.PC-ONT	99.97%	0.03%	10.58%	89.42%
PQ.QC-ONT	99.97%	0.03%	0.56%	99.44%
PQ.XY-ONT	99.93%	0.07%	50.33%	49.67%

In the final two columns of Table 4 we divide the cases of the same prices with respect to "trade" and "no trade" situations. Trade refers to the cases where the trade (either export or import) takes place between any two markets when the prices across the markets are equal to each other. As it is clear in the table that in the case of price equality, the dominant case is no trade, i.e. neither import nor export occurs in bilateral markets. For example, when Manitoba and Ontario prices are equal to each other, 99.7 per cent of the time in the study period no trade is observed between them. However this percentage is smaller in some markets, especially in some Quebec zones where it remains in almost 50 per cent. In this case an

[15] As is well known, the speed of price convergence is rather low when measured cross aggregate price indices or the same goods of different countries or regions.

interesting question arises: what would be the incentive for trade when there is no price differential between any two markets? Clearly the answer is pertaining to the supply, demand and the transmission capacity conditions in the two neighbouring markets, in which the electricity will flow from an excess production market to a high demand market obeying the transmission constraints between these markets.

It is clear from Table 4 that in most of the cases the prices are equal to each other in the bilateral markets considered above. However, exceptions arise especially in MansSk-ONT, Mich-ONT, Minn-ONT, and PQ.HZ-ONT bilateral markets, the prices are different in significant proportions. Therefore, it is worthwhile to analyze the characteristics of the trade when the prices between the markets are different. Table 5 aims to serve this purpose and displays the proportions of the imports and exports in the cases of different prices. This table further divides these cases into two categories: The price of trading market is higher (P+) or lower (P-) than that of the other market. For example, between the Man-ONT trade P+ refers to the situation in which Manitoba prices are higher than the Ontario prices.

Table 5: The proportions of export and imports when prices are different between any two markets.

	Export	**Import**	**Sum**	**Export**	**Import**	**Sum**	**Export**	**Import**	**Sum**
	Man-ONT			**ManSK-ONT**			**MICH-ONT**		
P+	0.071	0.029	0.100	0.291	0.005	0.297	0.189	0.008	0.197
P-	0.231	0.668	0.900	0.041	0.662	0.703	0.296	0.507	0.803
Sum	0.303	0.697	1.000	0.332	0.668	1.000	0.485	0.515	1.000
Regions	**MINN-ONT**			**NY-ONT**			**PQ.BD-ONT**		
P+	0.947	0.011	0.958	0.024	0.000	0.024	0.354	0.076	0.430
P-	0.011	0.031	0.042	0.129	0.847	0.976	0.231	0.339	0.570
Sum	0.958	0.042	1.000	0.153	0.847	1.000	0.585	0.415	1.000
Regions	**PQ.DZ-ONT**			**PQ.DA-ONT**			**PQ.HZ-ONT**		
P+	0.000	0.076	0.076	0.289	0.277	0.566	0.974	0.024	0.998
P-	0.022	0.902	0.924	0.145	0.289	0.434	0.002	0.000	0.002
Sum	0.022	0.978	1.000	0.434	0.566	1.000	0.976	0.024	1.000

Regions	PQ.HA-ONT			PQ.PC-ONT			PQ.QC-ONT		
P+	0.060	0.000	0.060	0.500	0.000	0.500	0.669	0.000	0.669
P-	0.109	0.831	0.940	0.500	0.000	0.500	0.331	0.000	0.331
Sum	0.169	0.831	1.000	1.000	0.000	1.000	1.000	0.000	1.000

Regions	PQ.XY-ONT		
P+	0.211	0.000	0.211
P-	0.737	0.053	0.789
Sum	0.947	0.053	1.000

When the prices are different, the sign of the price differences (P+ or P-) in principle should determine the direction of the trade across the bilateral markets. As it can be followed from Table 5, for instance, when the Manitoba and Ontario prices are different and they trade with each other, 10 percent of the time Manitoba prices happen to be higher than the Ontario prices (P+) and 90 per cent of the time Ontario prices exceed the Manitoba prices (P-). In partitioning the case of P+, we find that 7.1 per cent of the 10 per cent (that is 71 percent of the P+ cases) Ontario exports electricity to Manitoba, however in the remaining small periods Ontario imports from its counterpart. On the other hand, when the prices of Manitoba are lower than the Ontario prices (P-), the dominant trade form is the imports, which constitute 66.8 per cent of all cases and 74.2 per cent (=0.668/0.900) of P- cases. Therefore, for the Manitoba-Ontario trade, the direction of exports/imports is predominantly consistent with the sign of the price differences and we can conclude that the electricity trade occurs when regional prices are different; the electricity flows from the high price market to the low price market. As it can be followed from the table that the same conclusion can be drawn for the remaining markets, with some exceptions in Quebec zones whose sizes are relatively small.

Thus far we have examined trade patterns between the markets using their instantaneous actual prices. Since there is a lag between the decision to trade and the actual market prices, that is to say generators/traders commit to their trade positions before they observe the actual prices, for example importers in Ontario market must submit their bids (import quantities at certain price levels) to the IESO several hours before auction starts and they are scheduled one hour before the market clears, a natural question arises: do we expect to observe similar trade patterns in the case of price lags between any two trading markets? To address this question we repeat the above analysis reported in Tables 4 and 5 with different lags in the price differences up to 24 lags. We obtain qualitatively the same results as with those in Tables 4 and 5[16]. This implies that generators/firms/traders do not need to perfectly forecast the future price differences between the markets before they take their trade positions: it is sufficient to look at the past price differentials and their magnitudes to make trade decisions.

6. Concluding remarks

As electricity markets reform and open access transmission policies increasingly interconnect large territories, it becomes more and more imperative to understand how imports and exports influence local market prices. Due to the characteristics of electricity markets (such as non-storability, continuous match of demand and supply, transmission network constraints, and constantly changing demand and supply conditions), it is a challenging task to develop an electricity trade theory, as we attempted in Section 3. It can happen that electricity is exported from a high price market to a low price market; for instance, during an off-peak time New York exporters may sell electricity to a low price Quebec market. This may benefit both jurisdictions because New York exporters can recover their export costs and Quebec importers may avoid using power units with high start-up costs or simply save hydro resources for high priced future time periods. Also, in electricity markets simultaneous exports and imports, called wheeling through transactions, are possible. That is, even though prices are different in both markets a market participant can export electricity to other market and import into the home market at the same time. These factors complicate modelling trade behaviour among electricity markets/jurisdictions and estimating the trade effects on market prices. Even the most commonly used economic theory models, such as Cournot and Supply function equilibrium, may come short in explaining the relationship between trade behaviour and. Therefore, we empirically analyze the impact of trade in the Ontario wholesale electricity market using time series techniques. We employ several econometric techniques (event study, linear and nonlinear Granger causality tests) to analyze the trade activities between Ontario and its neighbouring jurisdictions in the network, and find that while Ontario exports cannot be unambiguously tied to the hourly Ontario energy prices, imports can. We have shown Granger causality for all lags in the case of imports with linear and non-linear tests.

[16] We do not report these results here to save some space. They are available upon request.

Our intertie analysis with the disaggregated high frequency data indicates primarily the price convergence between the trading markets in the network. Whenever prices differ between the markets the electricity mainly flows from the high price market to the low price market, although there are some exceptions which can be explained by the regional market conditions. Moreover, electricity traders (merchant firms and generation owners) can use observed price differentials between the markets to place their future trading bids. These findings may imply the strength of markets' integration in the network and suggest further investments in the interconnection lines would smooth the price spikes and reduce the cross-price differences. All of these would yield more efficient market outcomes facilitated by trade.

To fully grasp the network interactions and trade impacts on market price, more investigation is still required. Using additional empirical data sources (such as local loads in jurisdictions, network constraints data, and possibly other explanatory variables), as well as firm-level data, could be helpful to provide further insights. A trade analysis incorporating such data is a future research direction that one may consider. However, some of the data required, especially firm level data, is confidential and unavailable to public in some jurisdictions. In such cases, some approximation methods are still available.

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