Strategic Reneging in Sequential Imperfect Markets

Benatia, David and Billette de Villemeur, Etienne

HEC Montréal, LEM-CNRS (UMR 9221), Université de Lille

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David Benatia and Étienne Billette de Villemeur*

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Abstract

This paper investigates the incentives to manipulate markets by strategically reneging on forward commitments. We first study the behaviour of a dominant firm in a two-period model with demand uncertainty. We then use the model's predictions and a machine learning approach to investigate multiple occurrences of reneging on long-term commitments in Alberta's electricity market in 2010-2011. We find that a supplier significantly increased its revenues by strategically reneging on its capacity availability obligations, causing Alberta's annual electricity procurement costs to increase by as much as $600 million (+17%).

Keywords: Strategic Outages, Market Manipulation, Functional Data Analysis, Wind Curtailment

JEL Codes: D43, L12, L51, L94

*Benatia: HEC Montréal, 3000 Chemin de la Côte-Sainte-Catherine, Montréal, Québec, H3T 2A7, Canada (e-mail: david.benatia@hec.ca); Billette de Villemeur: LEM-CNRS (UMR 9221), Université de Lille, 3 rue de la Digue, 59000 Lille, France (e-mail: etienne.de-villemeur@univ-lille.fr). We are indebted to Allan Collard-Wexler for his guidance and three anonymous referees for their valuable comments and suggestions that greatly improved the quality of this work. We would also like to thank David Brown, Philippe Choné, Arnaud Dellis, Xavier D'Haultfœuille, Laurent Linnemer, Derek Olmstead, Pierre-Olivier Pineau, Steve Puller, Mar Reguant, Charles Séguin, Bert Willems, and participants to various seminars and conferences. This research is supported by a grant of the French National Research Agency (ANR), "Investissements d'Avenir" (LabEx Ecodec/ANR-11-LABX-0047).

1 Introduction

"Contracts are like hearts, they are made to be broken".[1] Failures to fulfill contractual obligations are indeed frequent. As parties recognize the risk of a contract "breach", they write clauses to protect themselves against certain contingencies but can hardly consider them all. In sequential markets, a contract breach may occur for legitimate reasons as, say, a shortage may force a supplier to renege on its promise to deliver some goods at a given date. Yet, insufficient penalties (or imperfect penalty schemes) imposed in case of such contingencies give rise to a moral hazard problem by leaving space for parties to renege on their commitments for strategic reasons. This moral hazard problem can have significant consequences in terms of efficiency and welfare distribution, especially in markets where prices are very sensitive to unexpected supply or demand shocks.

In this paper, we study strategic reneging in theory and practice. First, we develop a theoretical framework to analyze the behaviour of a dominant firm facing a competitive fringe in a two-period model with imperfect commitment and demand uncertainty. Second, we leverage machine learning to empirically investigate market manipulations, and to test our model's predictions, using a rich dataset about Alberta's electricity market in Canada. Our empirical analysis focuses on alleged occurrences of strategic reneging disguised under claims of "emergency" outages of power plants under long-term contracts. We use counterfactual strategies to estimate the welfare consequences and damages associated with market manipulation via contract reneging. A large supplier is found to have caused Alberta's annual electricity procurement costs to increase by as much as $600 million in 2010-2011. This firm and some of its rivals earned dozens of million dollars in extra revenues due to the large price impacts caused by the strategic conduct.

[1] So is reported to have said Ray Kroc, the fast-food tycoon who built the McDonalds empire.

Our theoretical framework aims at investigating how imperfect commitment interacts with market power in a sequential setting. We show that the decision to renege crucially depends on the residual demand. A less elastic residual demand causes the manipulation to have a larger price impact, while larger demand realizations increase the volume of spot sales which implies more leverage. We establish equilibrium predictions in order to provide guidance to detect strategic reneging, collect indirect evidence of potential misconduct, measure its consequences, and thus assess the need for regulatory intervention.

This framework shows that strategic reneging can be a *strategic substitute* or *strategic complement* to the mere exercise of market power, depending on market conditions. Reneging is thus not only an additional channel through which market power could be exercised, but is also a means to create, maintain, or enhance market power. This result underlines the broader role played by reneging in many electricity markets, even in absence of contractual commitments. In those markets, firms are forbidden to economically withhold large amounts of power through the bidding process. All firms can hence be considered as being committed to supplying close to marginal cost to comply with the regulation. Firms may thus attempt to escape this regulation by declaring an unnecessary maintenance outage so as to physically withhold power from the market. In other markets, like in Alberta, where market power is not prevented by regulatory protocols, outages can also be used to complement economic withholding.

In our model, the monopolist competes against a competitive fringe over two periods to supply a homogeneous good at a particular delivery time. Demand is random and assumed to be perfectly inelastic.[2] The residual demand curve is nevertheless elastic in both periods due to the presence of the fringe. In the first period, a share of the expected demand is allocated through forward contracts. The realized demand net of

[2]This is a reasonable assumption for electricity markets, where end-users are rarely faced with real-time prices. Relaxing it would not alter our qualitative results because it is not required for strategic reneging to occur.

these commitments is supplied in the second period on the spot market, where both production and consumption take place. The strategic reneging of commitments on the forward market weakens competition on the spot market to enhance the firm's overall profitability.[3] More precisely, by reducing its own output committed at forward prices, the firm increases the net demand in the spot market because the withdrawn output must be (at least partly) replaced in equilibrium. The residual demand curve is hence shifted which results in a spot price increase.[4] Strategic reneging is found to reduce the forward price premium, and can even *induce* price-convergence in equilibrium. We thus offer a new rationale for why the latter is no indication of market efficiency.

We test our model predictions and investigate the consequences of imperfect commitment in an application to Alberta's electricity market. This market provides several advantages to study strategic reneging. First, incentives to suppliers are relatively simple in Alberta's electricity market. Market outcomes are settled through a real-time auction, and there is no day-ahead auction (Olmstead and Ayres, 2014). Second, the market structure consists of a few large suppliers and many small firms, and market power execution is relevant as documented by Brown and Olmstead (2017). Third, the availability of firm-level bid data allows us to reconstruct residual demand functions and to test the theory. Fourth, the Alberta Market Surveillance Administrator (MSA) accused an incumbent supplier of market manipulations through strategically timed "emergency" outages of power plants subject to long-term forward contracts, in several instances from November 2010 to February 2011.[5] This case thus offers a rare opportunity to investigate strategic reneging empirically.

In our empirical analysis, we interpret these strategic outages as a type of strategic

[3]Carlton and Heyer (2008) defines this as extensive conduct in opposition to extractive conduct, e.g. the exercise of unilateral market power.

[4]Throughout this paper, we use "reneging" to refer to the act of not satisfying one's forward commitments to deliver some output.

[5]We focus on this case study that has been already thoroughly investigated both to illustrate how regulatory investigations are conducted and to avoid spreading erroneous accusations.

reneging on long-term forward commitments and evaluate their economic impacts. The compelling evidence collected in AUC (2015) makes clear that TransAlta's traders and plant operators collaborated to time outages. The report reveals that the firm had implemented a trading strategy that involved coordinating forced outages of power plants under long-term contracts and optimizing spot and forward strategies. The strategy also involved wind farms, under similar long-term fixed-price contracts, reducing output during periods of high wind to inflate wholesale prices.[6]

Our empirical investigation uses a sample of hourly observations containing firm-level bids, plant-level production, and market outcomes from November 2008 to August 2011. The analysis first documents evidence that the events coincided with high demand and low wind output periods. It also shows evidence that TransAlta's wind power production was curtailed for strategic reasons. Second, we show that the firm and its rivals have optimized their supply strategies during the outages. To do so, we leverage hourly firm-level bid data to predict supply and residual demand functions using a multivariate extension of the least absolute shrinkage and selection operator, or lasso (Simon, Friedman and Hastie, 2013). By predicting counterfactual strategies during reneging events (assuming outages did not occur) we can identify strategy shifts, compute counterfactual market outcomes, and therefore evaluate the impacts of manipulations. We find deviations of the firm's strategies in the spot market during the outages that are consistent with our model's predictions. By making use of its informational advantage regarding the outage timing, the firm's bids may reveal its intent to manipulate. Changes in supply bids may hence provide a red flag for regulators to detect potential misconduct early on, and intervene sooner.[7] Bidding strategies reflecting this inside information indeed deliver indirect proofs of intent, which, as we

[6]The complete regulatory proceedings are accessible from the Alberta Utilities Commission's eFiling System at `https://www2.auc.ab.ca/_layouts/15/auc.efiling.portal/login.aspx`.

[7]We do not study this timing aspect since our data is limited to final hourly bid offers and does not include information about whether hourly bids were modified.

argue, can be helpful for prosecution.

As we show in this paper, accounting for equilibrium effects yields greater estimates of manipulations gains and increases in procurement costs. We estimate that strategic reneging delivered up to $67 million in extra revenues to the firm, and up to $600 million in additional procurement costs for Albertans in 2010-2011. This represents a 17% percentage point increase in annual energy procurement costs in the province.

Finally, our paper provides both theoretical arguments and empirical evidence for the fact that, although long-term contracts are often considered as a channel to limit the exercise of market power (AUC, 2015), they may also create incentives for market manipulations with harmful consequences.

Related literature. This paper is related to the strands of economic literature on sequential markets, market manipulations, and market power in electricity markets. First, our framework draws from the durable good monopoly model of Coase (1972) which identifies a commitment problem. There is also a large literature in economics studying the role of various factors in the formation of price spreads between sequential markets (Weber, 1981; McAfee and Vincent, 1993; Bernhardt and Scoones, 1994). We focus on the role of imperfect competition, as in Allaz and Vila (1993) who show that sequential markets always improve efficiency. In contrast, we do not assume perfect arbitrage across markets and introduce an imperfect commitment problem. We find that, in the presence of contract incompleteness, sequential markets may be a source of manipulations and inefficiencies.

Our paper is related to Ito and Reguant (2016) who study arbitrage in sequential markets under imperfect competition and show that the conjunction of limited arbitrage and market power generates a forward price premium. We contribute to this literature by showing that the opposite result, i.e. a spot price premium, can arise in expectations because of imperfect commitment. We also complement their important insight about price convergence not being a reliable metric for assessing the degree of competition. In our setting, price convergence can arise because of multiple market failures: imperfect competition and imperfect commitment.

Second, this paper is related to the literature on market manipulations. Ledgerwood and Carpenter (2012) present a general framework of market manipulations with examples taken from financial and commodity markets. Strategic reneging can be interpreted as a form of loss-based manipulation in their framework. One of our main theoretical predictions is also in line with the general insight, found in the finance literature, that traders receiving inside information will re-optimize their strategy (Imkeller, 2003). Market manipulations typically involve collusion (Brown, Eckert and Lin, 2018; Dechenaux and Kovenock, 2007) or financial derivatives and transmission-related strategies in electricity markets (Birge et al., 2018; Lo Prete et al., 2019; AUC, 2012). Evidence of strategic timing of "emergency" outages of plants during tight market conditions also exist in European markets (Bergler, Heim and Hüschelrath, 2017; Fogelberg and Lazarczyk, 2019). We document similar evidence for Alberta and show that bid data can deliver further evidence of intent to manipulate and allow for a precise market impact assessment.

Third, there is a large literature on market power in the electricity industry. Borenstein, Bushnell and Wolak (2002) and Puller (2007) study the California electricity market, where suppliers scheduled plant maintenance during peak periods as a way to exercise market power. Empirical evidence of market power has been found in many electricity markets, including for capacity (Schwenen, 2015). In our application, we focus on the "emergency" maintenance of plants under forward contracts used as a manipulation device to extend unilateral market power in the spot market, but scheduled outages can also disguise strategic reneging in context where economic withholding is prevented by regulatory protocols. There is also a prolific amount of research about the role of forward contracts to mitigate market power. Although forward contracts are generally expected to be welfare-enhancing (Bushnell, Mansur and Saravia, 2008; Green and Le Coq, 2010), they may yield anti-competitive outcomes when firms are asymmetric (de Frutos and Fabra, 2012), or exacerbate intertemporal market power distortions (Billette de Villemeur and Vinella, 2011). This paper shows evidence that incomplete forward contracts can create incentives to dominant players for market manipulations with harmful consequences.

Fourth, there is a growing empirical literature using machine learning methods in microeconomic applications. Burlig et al. (2020) use causal inference for evaluating the gains of energy efficiency investments in K-12 schools in California. More precisely, they use a lasso approach as a way to construct the counterfactual energy consumption of each school assuming no investment had taken place. Benatia (2022) and Graf, Quaglia and Wolak (2020) study the COVID-19 pandemic's consequences for electricity markets in France and Italy, respectively. They use machine learning methods to obtain counterfactual predictions of electricity market outcomes in absence of containment measures.

Finally, strategic reneging is not limited to the supply side,[8] it can also occur outside electricity markets and take various forms. For instance, a company can schedule deliveries and cancel them at the last minute to withhold delivery capacities,[9] or it can refuse to honor a particular contract clause in order to foreclose competition.[10] Alternatively, the firm may force its competitors to renege on their contracts,[11] or even

[8]Faced with large electricity demand reductions caused by the pandemic in spring 2020, French distributors reneged on their regulated forward contracts, claiming force majeure, hence transferring their losses to the historical producer (Benatia, 2022).

[9]Marks et al. (2017) argue that electricity price spikes in New England have been caused by two companies regularly reneging on scheduled deliveries to withhold pipeline capacity. After due investigation, regulators have ruled that the companies followed normal industry practices.

[10]An antitrust investigation of the EU Commission has accused Gazprom to have strategically reneged on its obligations to accommodate changes of gas delivery points during a cold spell to ensure that Poland had "no choice but to cover the gas shortage by acquiring from Gazprom" (EUC, 2018).

[11]In a historical case, two potatoes producers were forced to default on their deliveries because of the scheme of a competitor which withheld all rail cars with phony deliveries, "leaving 1.5 million pounds of potatoes rotted because they could not be shipped out of Maine" (Markham, 1991).

renege as a means to disseminate misleading information.[12] Although our paper is built in reference to precise market manipulations in a specific context, namely that of Alberta's power market, we argue that the lessons learned extend much beyond.

Institutional details and the market manipulations in Alberta are presented along with the model in Section 2. The empirical study of Alberta's electricity market is developed in Section 3. Section 4 concludes the paper. All propositions and proofs are in Appendix A, additional empirical results in Appendix B, and inference is described in C.

2 Strategic Reneging in Electricity Markets

The outage of power plants under commitments can be used as a means to disguise strategic reneging in restructured electricity markets. We take advantage of the well-documented market manipulation events that occurred in Alberta's electricity market in 2010-2011 to better understand this phenomenon and develop a simple theoretical framework to guide our empirical study in Section 3. We begin by providing institutional details about the market and information about the manipulation events. We then develop a theoretical model and draw some lessons for regulation.

2.1 A Tale of Strategic Reneging

The Alberta electricity market. Alberta's electricity system is market-based since 2001. Competition has been introduced on the retail and wholesale segments of the industry, while transmission and distribution remained as regulated monopolies (Olmstead and Ayres, 2014; Brown and Olmstead, 2017). The Alberta Electric System Operator (AESO) is the authority mandated to design and operate the market. The

[12] "Spoofing" refers in financial markets to the posting and immediate reneging of quotes on electronic trading platforms is an observed practice that artificially increases trading activity and temporarily inflates the stock price (Hewitt and Carlson, 2019).

revenues of wholesale suppliers in this market consist almost only of payments collected from the short-run electricity market.[13]

The electricity market is organized as a uniform-price multi-unit procurement auction for each hour of the day. Suppliers submit offer bids one day-ahead of physical production to signal their willingness to produce different amounts of energy. Offer bids can be modified up to two hours before production. Generators must offer their available capacity in the market and can choose prices between $0 and $999.99 per MWh. Bids take the form of a (step) supply function with several price-quantity pairs for each generator. The AESO aggregates them into an industry-level supply function. The market-clearing price is determined at every minute and equals the highest accepted bid price to supply the realized electricity demand. Participants are paid the pool price, which is the time-weighted average price for each hour.

In 2011, power production in Alberta was dominated by thermal plants burning coal (46.9%) and natural gas (36%). The remainder of the production came from other energy sources such as wind (6.1%), hydro (6.1%), and other fossil fuels (4.9%) (Brown and Olmstead, 2017). Table 1 provides information with regard to Alberta's market structure and firm characteristics. In 2010-2011, the five largest firms controlled about 70% of market offers while the rest was controlled by a fringe of over 20 firms. Wind farms are not included in market shares because they receive fixed-price payments irrespective of market outcomes. Offer control differs from capacity ownership because of long-term bilateral contracts between suppliers.[14]

[Table 1]

[13]The Alberta electricity market is an energy-only market, meaning that there are no additional payment to suppliers to ensuring their profitability. In practice, some additional revenues can be obtained from supplying ancillary services to the AESO, such as short-term load balancing.

[14]One caveat of our bid data is that offer control was not well followed at that time. A few plants have multiple owners, each of which can submit bids for its respective share. Bid data is not differentiated in these cases, so we decided to split bids using information on offer controls from MSA (2012).

Long-term forward contracts. Power purchase arrangements (PPAs) are long-term contracts of up to 20 years introduced during the restructuring of Alberta's electricity industry in 2000.[15] The primary purpose of the PPAs was to anticipate potential market power issues caused by the concentration of capacity ownership within the hands of incumbent utilities. Before that, 90% of capacity was controlled by TransAlta, ATCO, and Capital Power. The contract leaves the ownership and operation of the assets to the owners but gives buyers the right to sell its production to the electricity market. This is essentially a "virtual divesture" for incumbents. In 2000, PPAs were sold in auctions with varying private terms including remunerations for fixed and operating costs, plus a rate of return.

The contracts give the buyer exclusivity to sell the facility's output up to a certain capacity, known as its committed capacity. For obvious reasons, the PPAs include incentives to owners to achieve the committed capacity. These incentives are referred to as availability incentive payments. If the available capacity is above a target specified by the contract, then the owner receives this payment. Conversely, if capacity is below the target the owner must pay this amount to the PPA buyer (AUC, 2015). The incentive payment is calculated as a 30-day rolling average of prices times the difference between the actual available capacity and the specified target.

We interpret those contracts as long-term forward commitments tied to some physical capacity. The plants subject to PPAs provide baseload production which is offered at low prices on the energy market by the PPA buyers.[16] The average offer price is around $15/MWh for PPA plants in our sample, and 74% of capacity is offered at $0/MWh, which is likely explained by the financial forward contracts by the suppliers.

[15] In the U.S., this type of contracts is generally called power purchase *agreements*, and is used for renewables.

[16] The energy is sold to a rival firm which then sells to the market. Assuming this rival to be price-taker (or with large forward covers) the energy would be offered at price p_1 in the spot as in our model. The main results are hence left unchanged. In a strategic setting, reneging would impact the rival's cost structure and further exacerbate the manipulator's market power.

For that reason, they almost always produce up to available capacity. The contract commits the owner to deliver whatever output the buyer might want up to target capacity. In this context, strategic reneging consists in choosing not to deliver the output by reducing available capacity below the contract target, at the cost of incurring the associated penalty. This conduct can be disguised under claims of maintenance needs, which might need to be substantiated if the regulator decides to investigate.

The allegations of market manipulations. The Alberta Market Surveillance Administrator (MSA) accused TransAlta Corporation of market manipulations through strategically timed "emergency" outages of its coal-fired power plants under PPAs in several instances from November 2010 to February 2011. After due investigation, the Alberta Utilities Commission (AUC, 2015) concluded that *"TransAlta unfairly exercised its outage timing discretion [...] for its own advantage and made its own portfolio benefits paramount to the competitive operation of the market"*. In other words, maintenance needs were not urgent and outages could have been delayed in order to prevent substantial market impacts. Ultimately, a $56 million settlement was made.

In the fall of 2010, TransAlta identified the complementarity of its supply strategy and forced outages of plants under long-term contracts to increase spot prices. The firm developed the *Portfolio Bidding Strategy* outlined in an (internal) executive summary dated October 21, 2010, after the hire of new senior trading personnel. The strategy's objective was to enlarge revenues from the spot market by increasing prices when the firm had a net selling position.[17] The main ingredients of that strategy involved to:

1. (Bidding) Optimize the bidding strategy in the spot and forward markets;

2. (Outages) Coordinate forced outages to optimize market impacts; and

[17] Besides, the firm considered that the price increase would drive forward prices up. This was expected to create arbitrage opportunities from undervalued forward contracts given the firm's private information about forced outages.

3. (Wind) Have wind farms to reduce output during periods of high wind.

The firm officially started to use this strategy on November 18, 2010. At the end of February, 2011, the MSA received complaints from Capital Power and ENMAX, two PPA buyers, regarding TransAlta's management of outages of its plants under PPAs.

The investigation conducted by the MSA focused on 4 main events: November 19-21, November 23, December 13-16, 2010, and February 16, 2011, involving a total of 6 forced outages of PPA plants. However, the witness statements reported in MSA (2014*a*) and MSA (2014*b*) indicate 7 additional events involving 12 other outages between November 2010 and August 2011. Details about the outages are provided in Table 2.

[Table 2]

The regulatory investigation. The regulatory proceedings include transcripts of communication between traders, managers, plant operators, and the PPA buyers (AUC, 2015), which illustrate three elements of misconduct. First, the evidence make clear that traders and plant operators collaborated to time the outages to maximize market impacts. After the event on November 23, 2010, a trader circulated an e-mail stating: *"Operations Manager for Sun 1/2, had called me on [November 22, 2010] afternoon about timing a 150 MW derate [...]. We determined to take [it] during the day for a price impact. [...] This was a great example of the ongoing coordination we have [...] to optimize outages"*. Second, some exchanges are suggestive of how traders optimized offer bids using the outage information. Following the event on November 19, 2010, a trader e-mailed his manager: *"Sun 5 came down early [...] and Poplar Creek pricing up, prices jumped to $400 over the peak hours."*, who replied *"[g]reat job this first week. Some great value and it's clear we're learning a ton."*[18] Finally, some transcripts reveal

[18]TransAlta owned and operated Sundance 5, a coal-fired power plant under PPA, and Poplar Creek, a 376 MW co-generation facility, at that time.

how deceitful TransAlta was with PPA buyers. For instance, on December 13, 2010, the PPA buyer called TransAlta's plant operator about the outage to ask if it could be postponed to which the response was: *"we have got a big boiler leak here, so it's the way it has to be here [...] they just had their big meeting out there."*. The expert audit will however reveal *"no indication these leaks were significant"* and that the *"repair could have waited until the following week-end"* (Heath, 2014).

The regulatory documents include six expert reports from engineers and economists. Heath (2014) and Eisenhart (2014) establish that the timing of those forced outages were contrary to the common practice and industry customs in Alberta, and more generally in North America. They review the details of all the forced outages and provide expert evidence that it would have been feasible to move the outages to the next week-end or the next planned outages without any increase in risk of further equipment damage or endangering the safety of plant personnel.

Church (2014) presents a qualitative framework based on the competition policy and economics literature to evaluate the effects of the alleged behaviour on market competition. The analysis focuses on the distinction between conduct that involves the exercise of unilateral market power versus conduct that creates, maintains, or enhances market power. This distinction between *extractive* conduct and *extensive* conduct (Carlton and Heyer, 2008) is key to determining whether the behaviour is deemed anti-competitive because market power exertion is not prohibited in Alberta's electricity market. Church (2014) considers TransAlta's conduct as anticompetitive because it can make economic withholding, i.e. unilateral market power, more effective. The report concludes that the behaviour was anticompetitive because it removed cheap supply in peak periods, forcing market participants with prior commitments to buy at larger prices on the spot market. These insights are confirmed by our theoretical and empirical analyses. Falk and Shehadeh (2014), acting as experts hired by TransAlta, disagree that forced outages should be considered as anticompetitive, notably because the firm followed the economic incentives specified in the PPA contracts.

Ayres (2014) consists in the MSA's quantitative evaluation of the price impacts during the 4 main events. The analysis uses alternative timings for the outages based on Heath (2014) and Eisenhart (2014) and study spot and forward prices separately. The report finds potential transfers from consumers to suppliers ranging from \$13 million to \$137 million, depending on the counterfactual scenarios. The methodology and its limitations, some of which pointed out in Frayer (2014), a consultant hired by TransAlta, will be further discussed in our empirical analysis.

We interpret strategically timed forced outages of plants under PPAs as a form of strategic reneging on long-term forward commitments. The firm purposefully restrained production from the assets under contracts to benefit its portfolio position at the cost of the foregone revenues and contract penalties. Note that the plants were always undergoing actual technical issues although not as urgent as claimed by the firm. In this respect, the urgency of maintenance requirements is difficult to monitor for regulators, rival suppliers, and retailers alike.

2.2 Theoretical Framework

Let us develop a theoretical framework to better understand the incentives and implications of this strategic conduct from a general perspective. We model a dominant supplier facing a fringe of competitive firms in a sequential market with stochastic demand. Although TransAlta is one of a group of oligopolists in Alberta, an alternative modeling of imperfect competition would not modify the main insights about how strategies are shifted when reneging occurs. In our empirical study in Section 3, we find that one of the main contributors to the spot price impact of reneging is often the strategic response from rival generation suppliers. This response, which is not part of the theoretical model we present here, suggests additional channels through which strategic reneging may enhance market power.

This framework has the following testable implications for the empirical part: 1) strategic firms will shift their supply upon reneging; 2) the elasticity of residual demand is the key factor to compute the size of these strategy shifts, price impacts, and output impacts; 3) reneging and unilateral market power can substitute or complement each other to create a market impact; 4) they are strategic complements only if the residual demand function is very inelastic, or exhibits discontinuities.

We first present the general setup, and develop the benchmark case (without reneging), before introducing reneging and discussing the results. For simplicity of exposition, we collect all formal propositions in Appendix A in order to focus on the interpretation of our results in the main text and save space for the empirical part.

2.2.1 The Setup

Let us consider a sequential market organized in two periods. The forward market takes place in period 1 and the spot market occurs in period 2. Both production and consumption take place in period 2. Final demand is a random variable A realized in period 2, and which distribution $F(\cdot)$ is supposed to be known. Demand is observable and perfectly inelastic to prices in the spot market. In period 1, buyers choose to contract an exogenous share $\alpha > 0$ of the expected demand $E(A)$ through forward commitments.[19]. They hence buy $A - \alpha E(A)$ in the spot market. In electricity markets, $\alpha E(A)$ can represent monthly forward contracts of load-serving entities, or long-term bilateral agreements like PPAs in Alberta.[20] For clarity, we assume that arbitrage across markets is not possible.[21]

[19] Making α endogenous requires assumptions about the risk aversion of buyers and their degree of coordination. We opted for not introducing such assumptions and offering results that are valid for any α. Some additional results with α endogenous are presented in Proof 2 in Appendix A

[20] Buyers sell back their extra commitments in the spot market if $A < \alpha E(A)$.

[21] Most of the literature considers at least some degree of arbitrage between spot and forward prices. We assume away arbitrage because i) it would only affect the level of demand above which reneging is profitable, and ii) our empirical study focuses on the PPA contracts which are long-term commitments.

A dominant supplier competes against a competitive fringe on the supply-side. Let Q_t and q_t be the quantities sold by the dominant firm and the fringe, respectively, in period $t \in \{1, 2\}$. For each player, the total quantity produced is denoted $Q = Q_1 + Q_2$ and $q = q_1 + q_2$, respectively. To gain intuition, we specify linear marginal cost functions as $C(Q) = Q/B$ for the monopolist and $c(q) = q/b$ for the fringe. The hypothesis of price-taking behaviour implies that the fringe's supply in period 1 is $q_1 = bp_1$, whereas $p_2 = (q_1 + q_2)/b$ because the whole production takes place in period 2 so that $q_2 = b(p_2 - p_1)$.

2.2.2 Sequential Markets under Uncertainty

Residual demand. In period 1, the demand $\alpha E[A]$ is covered. The residual demand faced by the monopolist is $D_1(p_1) = \alpha E[A] - bp_1$, meaning that in equilibrium

$$Q_1 = \alpha E[A] - bp_1 \tag{1}$$

must hold. Similarly, the equilibrium quantity sold on the spot market by the monopolist must be such that

$$\begin{aligned} Q_2 &= A - \alpha E[A] - q_2 \\ &= A - \alpha E[A] + b(p_1 - p_2). \end{aligned} \tag{2}$$

Spot market sales depend on the difference between realized demand A and total commitments $\alpha E[A]$, as well as the price spread $p_1 - p_2$, following the fringe's adjustment on the spot market.

Monopolist problem. The expected profits of the dominant firm, hereafter referred to as the monopolist, can be written

$$E[\Pi] = p_1 Q_1 + E[p_2 Q_2] - E\left[\int_0^{Q_1+Q_2} C(Q)dQ\right], \tag{3}$$

where the expectation is taken with respect to A, and the prices p_1 and p_2 are determined by the equilibrium conditions (1) and (2). The monopolist maximizes profits by backward induction. Taking forward commitments as sunk decisions, the profit-maximizing spot sales upon observing A are denoted by $Q_2^\star$. In the first stage, the monopolist anticipates its behaviour in the spot market and maximizes its expected profits defined in (3). Its equilibrium forward commitments are denoted $Q_1^\star$.

In equilibrium, the monopolist's commitments and final output are positively related to the level of demand and its relative competitive advantage (Proposition 1).[22] Positive price-cost margins in the spot market are observed when the monopolist is a net seller. Furthermore, there is a forward premium, that is $p_1^\star - E[p_2^\star] > 0$, if and only if the monopolist is a seller in the forward market. This occurs when consumers choose a large enough degree of forward contracting. Hereafter, we assume $\alpha > \underline{\alpha}$ so that the monopolist is always a seller in the forward market, like TransAlta which was a PPA seller in our application.

2.2.3 Strategic Reneging

The monopolist is now given the ability to renege on some of its forward commitments upon observing A. In practice, reneging may occur for legitimate reasons, for instance as a consequence of technical failures, or for strategic purposes. It is nevertheless costly to verify the legitimacy of supply disruptions and thus whether they constitute a contract breach or even a fraud.

In this paper, we assume the institutional framework to fully ignore the possibility of reneging not being legitimate. This is, of course, an extreme assumption.[23] However, as long as strategic reneging cannot be completely prevented, there will be deviations

[22] In addition to being the slope of the residual demand, recall that b is inversely related to the fringe's marginal cost.

[23] An alternative model under asymmetric information would assume two states of the world (true failure or not) which realizations are unobservable by the principal. Although we do not pursue in this direction here, the main insights would be unchanged as long as institutions remain imperfect.

in equilibrium under imperfect information.[24]

Let $\mu \in [0,1]$ denote the share of commitments that can be reneged upon because the firm has a "good excuse" to do so. In our application, μ represents the share of contracts tied to specific production assets for which the firm can credibly claim an emergency outage requirement.[25] Those contracts commit the assets to the physical production of μQ_1 in period 2. Let $R \in [0, \mu Q_1]$ denote the "reneged output", i.e. the amount that the monopolist chooses not to produce although initially committed.

The unsatisfied demand R must be served in the spot market.[26] The forward price remains unaffected because it has already been settled. However, reneging affects the price in period 2 as it shifts upward the residual demand curve faced by the monopolist. More precisely, the spot price is now determined by

$$p_2 = \frac{1}{b}\left(A - (Q_1 - R) - Q_2\right). \tag{4}$$

Remark that this framework is easily adapted to situations where firms are forbidden to economically withhold large amounts of output. In many electricity markets, plants must sell their energy around benchmark prices, typically marginal cost estimates, chosen by the regulator. The first period of our model would then represent the firm's commitment to comply with this regulation by supplying at marginal cost. The firm is able to escape this regulation by scheduling an outage to lower its output and reach higher prices in equilibrium.

[24]For instance, Green and Porter (1984) show that the optimal incentive structures in collusive equilibria typically involve episodic deviations from collusive conduct.

[25]In our study of Alberta's market, the firm exaggerated minor technical problems reported by plant operators to substantiate claims of emergency outage requirements. Technical failures occur randomly and somewhat independently of market conditions. The probability of facing a technical failure can however be attenuated with planned maintenance, higher reserve margins, and lower use rates (Kim et al., 2020).

[26]More generally, this effect could also be the result of reneging in a different market (Marks et al., 2017), or due to the refusal to honor a contract clause (EUC, 2018), or even caused by a scheme forcing some rival firm to default on its delivery obligations (Markham, 1991).

Spot market. Contracts typically account for the possibility of non-delivery. Let τ represent a per-unit deviation penalty that is contractually binding.[27] In period 2, the monopolist solves the profit-maximization problem

$$\max_{Q_2,R} \quad \Pi = p_1(Q_1 - R) + p_2 Q_2 - \int_0^{Q_1-R+Q_2} C(Q)dQ - \tau R, \tag{5}$$

jointly with respect to Q_2 and R taking Q_1 as given.[28] The profit-maximizing spot sales are denoted by $Q_2^\dagger$, when reneging occurs. As long as $Q_1 > 0$, reneging $R > 0$ leads to an increase of the profit-maximizing volume of sales in the spot market $Q_2^\dagger = Q_2^\star + \Delta Q_2$, with $0 < \Delta Q_2 < R$.

The commitment problem essentially arises from a contractual failure. A natural solution is to penalize any deviation by $p_2 - p_1$. Doing so makes the firm financially accountable for its deviations, which would prevent any strategic reneging in equilibrium.[29] This penalty can, however, put too much risk on the seller in a situation where actual technical problems are bound to happen.

We find that demand must be sufficiently large for this conduct to be profitable (Proposition 2), and is hence more likely during peak periods. Moreover, increasing the amount of commitments allows to shift the residual demand further to the right upon reneging, which results in a greater likelihood of a profitable manipulation.

Reneging incentives. The optimal strategy can be characterized by comparing the profits obtained in each case. For a given realized demand A, let us denote the ex-post

[27] We will see that this linear contract leads to imperfect commitment. In a more general model, the availability of a "good excuse" μ would be random. The optimal τ would hence be determined together with p_1 as functions of the distributions of μ and A, and the cost of auditing.

[28] If reneging implies that some low-cost generating capacity is unavailable then this formulation would tend to overstate the benefits of reneging to some degree, as it would not recognize that this capacity will not available for spot market production. The cost function should be changed to $\int_0^{Q_1+Q_2} C(Q)dQ - \int_{Q_1-R}^{Q_1} C(Q)dQ$.

[29] This corresponds to financial forward contracts. Substituting τ by p_2-p_1 in (5) yields $Q_2^\dagger - Q_2^\star = R$, hence p_2 is unchanged in equilibrium and the problem vanishes. However, in a supply function auction with binding capacity constraints, no finite penalty can fully deter strategic reneging (Benatia, 2018*a*).

profit when commitments are satisfied by,

$$\Pi^\star(A) = p_1 Q_1 + p_2^\star Q_2^\star - \int_0^{Q_1+Q_2^\star} C(Q)dQ, \tag{6}$$

and, the profit when the firm reneges on μQ_1 by,

$$\Pi^\dagger(A) = p_1(1-\mu)Q_1 + p_2^\dagger Q_2^\dagger - \int_0^{(1-\mu)Q_1+Q_2^\dagger} C(Q)dQ - \tau\mu Q_1. \tag{7}$$

Reneging is profitable for all A such that $\Pi^\dagger(A) - \Pi^\star(A) \geq 0$, that is when

$$\Delta p_2 Q_2^\star + p_2^\dagger \Delta Q_2 + \Delta C \geq (p_1+\tau)\mu Q_1, \tag{8}$$

where $\Delta p_2 = p_2^\dagger - p_2^\star$ is the *price impact*, $\Delta Q_2 = Q_2^\dagger - Q_2^\star$ denotes the *strategy shift* on the spot market and *the cost savings* are $\Delta C = \int_{(1-\mu)Q_1+Q_2^\dagger}^{Q_1+Q_2^\star} C(Q)dQ$.

The condition (8) sheds light on the benefits and losses associated with reneging. On the one hand, the scheme involves incurring the penalty cost τ as well as the opportunity cost p_1 for each reneged unit. On the other hand, it affects the strategic player's profits through thre channels (Proposition 3). First, it affects the (spot) market-clearing price upwards, $\Delta p_2 \geq 0$. This revenue corresponds to the intensive margin, that is the increased profit margin on the spot sales. The less elastic the *residual* demand, the larger this effect. Second, the spot sales are adjusted upwards, $\Delta Q_2 \geq 0$, which will give more leverage to the manipulation. The less elastic the *residual* demand, the smaller this effect. This effect is on the extensive margin. Finally, there may be some cost savings.

The elasticity of the residual demand faced by the firm is the key determinant of the strategy shift, the price impact, and potential cost savings. In any case, reneging on the quantity supplied on the forward market is associated with an increase in supply on the spot market, hence reneging is an additional channel through which market power could be exercised. In other words, the mere exercise of market power and reneging can be considered as strategic substitutes. We will see shortly that they can also reinforce each other.

Forward market. In period 1, the expected profit maximization program is changed into

$$\max_{Q_1} \quad E[\Pi] = \int_0^T \Pi^\star(A)dF(A) + \int_T^{+\infty} \Pi^\dagger(A)dF(A). \tag{9}$$

The gains from reneging increase with Q_1, and the profit-maximizing forward position will be larger if the monopolist anticipates that reneging will be profitable with positive probability (Proposition 4). More importantly, there is a range of forward covers $[\underline{\alpha}, \overline{\alpha}]$ for which a spot price premium is sustained in equilibrium (Proposition 5). This result shows the limit of using price convergence as a metric to measure competitiveness in sequential imperfect markets.[30]

Discontinuous residual demand. Residual demand functions are seldom linear in the real world. For example, in the application, the observed residual demands are step functions because of the multi-unit auction design. We thus extend our results to (discontinuous) piecewise linear functions. Let the fringe's marginal cost function be modified to $c(q) = q/b + \Delta c$ for $q \geq k$, and be unchanged for $q < k$. The dominant supplier is paid the spot price $p_2 = (A - Q_1 - Q_2)/b + \Delta c$, where $\Delta c > 0$ is the step size, if its output is $Q_2 \leq Q_2^k = A - Q_1 - k$.

In the linear setting, strategic reneging always coincides with a positive strategy shift to $Q_2^\dagger - Q_2^\star > 0$. The existence of discontinuities gives rise to a different situation where it is sometimes profitable to renege on commitments and *reduce* output below $Q_2^\star$ to trigger the price step. This occurs for levels of demand smaller than the threshold T

[30] This point was already made by Ito and Reguant (2016) in a setup with market power and limited arbitrage. In their setting, more arbitrage leads to more competitive outcomes on average but enlarges the deadweight loss during periods where the strategic player enjoys high market power.

characterized in the linear case (Proposition 6). We identify two main implications.[31] First, discontinuous residual demand functions facilitate strategic reneging because it is now profitable at lower demand levels. Second, the exercise of market power and strategic reneging can complement each other to create a price impact. Indeed, a negative strategy shift would *not* be profitable *without* reneging. Therefore, a supply-cut on the spot market coincidental with reneging may be due to strategic manipulations, because market power and reneging can be strategic complements.[32]

2.3 Lessons for Regulation

The model delivers important insights for regulation. Identifying and proving a manipulative behaviour is not a trivial task. It entails providing evidence of the manipulation and the intent to manipulate, as well as the creation of a price impact caused by the alleged manipulation. Let us consider that a firm has strategically reneged on its commitments under (false or exaggerated) claims of a production failure or maintenance outage requirements. From (8), the rewards from the manipulation are

$$\Big(\Delta p_2 Q_2^\star + p_2^\dagger \Delta Q_2 + \Delta C\Big) - (p_1 + \tau)R. \tag{10}$$

The profitability depends on the reneged output R and its associated cost $p_1 + \tau$, the production costs reduction ΔC, the ex-post price $p_2^\dagger$, the strategy shift ΔQ_2, the price impact Δp_2 and the counterfactual sales $Q_2^\star$ assuming reneging had not occurred. In principle, this formula can be used to estimate the disgorgement penalties. Unfortunately, estimates of Δp_2 and $Q_2^\star$ may be the subject of contention. Furthermore, benefiting from a supply disruption or even causing a price impact is not satisfactory

[31] Proposition 6 summarizes the results for the case where the discontinuity jump is at the left of the profit-maximizing output in the linear setting, i.e. $Q_2^k < Q_2^\star$.

[32] Some implications of large discontinuities in residual demand functions are discussed in Brown and Eckert (2021).

proof of intent. Reneging can occur for legitimate reasons and contracts usually account for the possibility of non-delivery.[33] Additional evidence need usually be collected through audits performed ex-post, as in the case of our empirical application.

The auditing costs and limited investigation capacities tend to reduce the scope of regulatory interventions to outright manipulation cases, or following a denunciation. In our application, the strategic manipulations could have escaped the regulator for long, had they not significantly harmed several (large) rival suppliers in February 2010. The theoretical predictions of our model deliver potential red flags and additional proofs of intent which can be helpful to motivate inquiries into more surreptitious cases. According to the model, the occurrence of a reneging event is more likely to be of strategic nature if it coincides with tight market conditions (e.g. peak demand, inelastic residual demand, or low wind output); but also if the firm's strategy on the spot and forward markets differ from usual, and reflects that the supply disruption was anticipated. We argue that, in such a case, the observed adjustments constitute indirect evidence of intended market manipulations.[34].

In practice, there are often delays between market closure and the time at which market outcomes are settled. In most electricity markets, offer bids must be submitted by market participants several hours before actual production, leaving room for an emergency outage to be declared close to or after market closure. "Abnormal" bids, e.g. those exhibiting a sudden shift, before the outage declaration actually *reveals* either its strategic nature or that the firm concealed information about the upcoming occurrence of a (legitimate) forced outage. In either case, the bids provide proof of misconduct.

Therefore, the regulator can not only use causal estimates of price impacts but also

[33]Reneging under a claim of a technical issue is not legitimate if the claim cannot be substantiated (e.g. the technical failure was exaggerated, or reported later so as to time the non-delivery).

[34]As an enforcement matter, the timing of bids (though unobserved in our data) accounting for the outage information relative to actual outage declaration can be a valuable piece of information.

obtain estimates of counterfactual strategies to evaluate whether further investigation is needed. Even though regulators have been reluctant to prosecute based on statistical inference in the past, they are now increasingly using data for market oversight.[35]

3 Empirical Analysis of Strategic Reneging

Let us turn to the market manipulation events that occurred in Alberta. We begin by providing a description of the data used before performing a preliminary analysis of the events. Finally, we propose an in-depth analysis of the firm's conduct and an assessment of the market outcomes and welfare impacts.

3.1 Data

We use data shared by the AESO and the MSA,[36] and historical weather data collected from Environment Canada.[37] The market data contains daily natural gas prices (AECO-C), hourly spot prices, loads, import and export capacities, wind farms' outputs, temperature series in Calgary, Edmonton, Vancouver and Saskatoon, as well as generator-level information such as hourly bids, available capacity, and dispatch indicators.[38] The complete dataset spans from November 1, 2008 to September 1, 2011. The four main events, as investigated by the MSA, took place between November 1, 2010 and March 1 2011, but the witness statements also include allegations about seven events that occurred up to August 2011, for a total of 18 outages, as shown in Table 2.

Observed firm-level bid functions have between 20 and 30 price-quantity pairs. To

[35]For instance, the FERC's investigation into Constellation's virtual trading activities in New York's electricity market was initiated following observations of "bizarre price behaviour" by the Division of Energy Market Oversight (FERC, 2012).

[36]We are grateful to Derek Olmstead for sharing this dataset with us.

[37]`https://climate.weather.gc.ca/historical_data/search_historic_data_e.html`

[38]Bids include domestic generation as well as export/import offers to adjacent regions. At the time, there were no demand-side bidders but some responsive load (about 3% of average demand) for a total of 245 MW. We account for this feature following Ayres (2014).

simplify the numerical analysis and take advantage of functional data analysis methods, we project all observed bids onto a finite grid of 52 equi-spaced prices from \$0 to \$1000. As a preliminary step, we approximate each observed bid function as a 52-dimensional vector of quantities defined over this fixed price grid.

The data is divided into two main sets of hourly observations where strategies tend to be more similar, informally referred to as peak (07:00 to 21:00) and off-peak hours (21:00 to 07:00) in the rest of the paper. The machine learning models are trained and evaluated on different data splits. All hourly observations where reneging occurred during the same day are assigned to one of two "reneging sets": main events or additional events, which corresponds to the events in Table 2. The remaining sample is split into a training set and a testing set. The training set is used to estimate the models whereas the testing set is used to evaluate its predictive power. Sample splitting is done randomly so that the training (testing) sample has roughly 70% (30%) of observations.[39] Table 3 provides summary statistics of the main variables for peak and off-peak hours in each subsample. The mean and standard deviations are relatively close between the training and testing samples. Demand and prices are noticeably larger during outage events. TransAlta's mean quantity bid across prices is smaller during outages whereas the residual supply is on average larger.

[Table 3]

The historical weather data from Environment Canada include 167 weather stations with hourly data located in Alberta. In our empirical analysis, we use 53 stations for which the series have a limited number of missing values.[40] We extract 52 temperature series, 46 dew point temperature series, 46 humidity series, 33 windspeed series, and

[39]Different random splits of the data gave quantitative results no larger or smaller than 0.5%.

[40]We use shape-preserving piecewise cubic spline interpolation to fill missings when the series have less than 15 consecutive missing hourly observations. The series are otherwise discarded from the sample.

17 wind angle series, for a total of 194 weather variables. Table B1 in Appendix B shows summary statistics about these variables and weather stations.

3.2 Strategic outages and wind curtailment

We begin by documenting what features are correlated with the occurrence of the strategic forced outage events. Then, we investigate whether the firm curtailed wind power production strategically.

Strategic timing? First, we investigate whether the outages occurred under tight market conditions. We regress a binary variable $\mathbb{1}_t^{outage}$ equal to one in hours during outage events on a set of explanatory variables capturing market conditions. Our objective is to characterize whether demand and wind conditions were unusual during the outage events, after conditioning on time fixed-effects. We estimate the following equation by OLS

$$\mathbb{1}_t^{outage} = \beta_1 D_t + \beta_2 W_t + \alpha' X_t + u_t, \tag{11}$$

where controls include the system demand D_t, total wind output W_t, and a set of time fixed-effects X_t, for hours of the day, days of the week, months, and years. Table 4 shows the estimation results for 4 different set of events. Columns 1 & 2 focus on the main outage events investigated by the MSA and use the period from November 2010 to August 2011. The outage variable is equal to one respectively during the first 4 hours of each event (column 1) and all hours of each event (column 2). The mean of the dependent variable is 12 times larger in the second regression. Columns 3 & 4 focus on the outages of duration between 4 hours to 7 days that occurred between November 2008 and November 2010, that is before the Portfolio Bidding Strategy was implemented. The outage variable is equal to one during the first 4 hours of each outage (column 3), and all hours of each outage (column 4). We only report the two main variables of interest.

[Table 4]

The main events (columns 1 & 2) are found to coincide with tighter market conditions on average, with larger demand and less wind power. The outages before November 2010 (columns 3 and 4) are not found to be associated with tighter market conditions. These results suggest that TransAlta have timed its outages based on market conditions. As pointed out by Capital Power in its witness statement (MSA, 2014*a*): *"in and around November 2010, it appeared that [...] TransAlta had begun taking a different approach to the scheduling of outages at PPA units. [...] For example, the outage would start during a peak period on a weekday."* Our results also show that the outages also spanned over periods where demand net of wind power was unusually large.

Strategic curtailment of wind power? The firm's trading strategy described earlier involved the strategic curtailment of wind farms. We investigate whether this strategy was effectively implemented by estimating the following linear model

$$W_t^{TA} = \beta_1 \mathbb{1}_t^{reneg} + \beta_{ws}' WS + \beta_{EN}' W_t^{EN} + \beta_{SU}' W_t^{SU} + \alpha' X_t + u_t \tag{12}$$

where W_t^{TA} is TransAlta's aggregate wind power production. We control for wind conditions using wind power output from the wind farms owned by ENMAX (2 plants) and SUNCOR (2 plants), denoted with W_t^{EN} and W_t^{SU}, and 4 wind speed series from the closest weather stations, denoted WS.[41] We also include a constant, a linear time trend, and fixed-effects for hour of the day, day of the week, and months, and years.

[41] We only keep wind farms for TransAlta (4 plants) and its competitors that were in operation during the entire sample. The stations are located between 3 km and 23 km away from the wind farms.

The binary variable $\mathbb{1}_t^{reneg}$ represents the treatment of interest. We estimate two average treatment effects. First, we focus on whether the Portfolio Bidding Strategy had an impact on wind power production by setting $\mathbb{1}_t^{reneg}$ to zero before November 1, 2010, and equal to one after. Second, we focus on the outage events in Table 2 and define one treatment variable equal to one during the main outage events and another treatment variable equal to one during the additional outage events (and zero otherwise).

Table 5 reports the results for the two treatment effects in columns 1 and 2. As a robustness test, the second treatment is also separately estimated (columns 3 and 4) for ENMAX and SUNCOR, the only two rival firms which also operated wind farms at the time, controlling for TransAlta's output. We find that TransAlta's hourly wind output was on average lower by 3.65 MW (-7%) after the implementation of the Portfolio Bidding Strategy under similar wind conditions. More importantly, TransAlta's wind farms produced on average 10.22 MW less (-20%) during the main events, than under similar wind conditions. The average effect during additional events is not statistically significant. We find that none of these effects are significant for the rival firms (columns 3 and 4).

[Table 5]

These results show evidence of significant output anomalies from the wind farms owned by TransAlta after November 2010 and even more so during the outages investigated by the regulator. We consider this as evidence that the firm engaged in strategic wind curtailment.[42]

Long-term renewable contracts, like feed-in tariffs, do not impose delivery obligations. For this reason, the curtailment of renewable power is a means to "renege" that

[42] Due to the inherent difficulty to predict wind power production, a more precise empirical analysis would require more granular weather and wind power data.

is always possible and rarely costly. Therefore, these contracts provide firms with a free market manipulation channel, which should draw attention from regulators and market designers.

3.3 Machine Learning from Bids about Manipulations

The regulator's assessment of price impacts relies on a simple methodology (Ayres, 2014). It consists in adding the generation that was not available and keeping all the rest constant to calculate counterfactual market outcomes – as if no market participant had reacted to the outage by changing their bids. The report also considers a variety of refinements including the modeling of exogenous import/export and demand-response functions, which we replicate in our analysis, and a comparison of the historical bids for some generators in an attempt to accommodate the potential dynamic reactions of TransAlta and its competitors. Frayer (2014), a consultant hired by TransAlta, considers this latter aspect of the analysis as "unreliable", arguing that firms have greatly modified their behaviours in response to the outages. In particular, she shows that competitors reacted to the outage on November 19, 2010 by offering their capacity at larger prices, and argues that such *"behaviour of economic withholding is a form of competitive reaction to the supply situation triggered by the outage"*. Our methodology is aimed at addressing these limitations.

We propose to quantify the strategy shifts from TransAlta and its competitors during reneging events using a predictive model.[43] We first develop a machine-learning approach to compute counterfactual strategies which can be used to identify potential misconducts, derive counterfactual market outcomes, and evaluate welfare consequences. Instead of proposing a structural model, we opt for a predictive model of the firm's strategy under business-as-usual conditions, i.e. in absence of strategic reneging.

[43] The title of this section is a reference to Burlig et al. (2020) which inspired our empirical approach.

Our preference for a predictive approach in this context is motivated by two main reasons. First, the major advantage of the structural approach is to be able to simulate counterfactual outcomes under different structures that have never been observed in practice, such as a prospective change in market design. Our objective is, instead, to predict strategies and market outcomes under business-as-usual conditions, assuming reneging had not happened.

Second, the framework developed in Section 2 provides helpful indications about what to look for in the data. Nevertheless, it lacks too many important elements to be used as a structural model. The structural approach requires imposing behavioural assumptions and choosing an equilibrium concept. The actual game played in Alberta's electricity market is a supply function auction with capacity constraints under uncertainty, choosing an equilibrium concept is hence not trivial.[44] While the Cournot model has been found to apply reasonably well to Alberta (Brown and Olmstead, 2017), it assumes elastic residual functions and quantity strategies that cannot explain the negative supply shifts predicted in Proposition 6. In comparison, the predictive approach does not require an equilibrium concept, works with complex strategy spaces (here supply and residual demand functions), and can even capture the tendency of some firms to act sub-optimally without imposing behavioural assumptions (Hortaçsu et al., 2019). This approach also has its limits: it relies on an identifying restriction, which is discussed in due time.

Empirical strategy. Let us denote TransAlta's observed supply and residual demand functions by S_t and RD_t in hour t, i.e. $S_t(p)$ is the quantity supplied by the firm in hour t if the equilibrium price is p. Following our model's notations, let $(S_t^{\dagger}, RD_t^{\dagger})$ and $(S_t^{\star}, RD_t^{\star})$ be the potential outcomes with and without reneging, respectively. However, both potential outcomes $(S_t^{\star}, RD_t^{\star})$ and $(S_t^{\dagger}, RD_t^{\dagger})$ are never observable for

[44] Holmberg and Wolak (2018) provides a theoretical framework tailored to this context.

the same hour. We propose to train predictive models for $(S_t^\star, RD_t^\star)$ so as to derive counterfactual estimates during reneging events $(\widehat{S}_t^\star, \widehat{RD}_t^\star)$. These estimates reflect the market conditions that would have prevailed in absence of reneging. The estimated strategy shift is defined as

$$\widehat{\Delta S}_t(p) = S_t(p) - \widehat{S}_t^\star(p), \tag{13}$$

for every price $p \in [0, 999.99]$. It corresponds to the *individual* treatment effect of reneging during "reneging hours" (treatment), and predictions errors during "normal hours" (control).

The (observed) residual demand function is directly impacted by reneging as it makes part of the supply committed at forward prices unavailable. In addition, the function can also be impacted by a reaction from competitors to the supply disruption. The estimated change in residual demand function, defined as $\widehat{\Delta RD}_t(p) = RD_t(p) - \widehat{RD}_t^\star(p)$, accounts for both effects. To test for the presence of competitors' reaction to the supply disruption, we construct an alternative counterfactual residual demand function based on the approach in Ayres (2014). The latter assumes that i) no strategic reaction was caused by reneging; ii) the withheld capacity would have been offered at zero prices (as observed in the data).[45] It is defined as $\overline{RD}_t(p) = RD_t(p) + \sum_{r \in \mathcal{R}_t} k_r$, where k_r denotes the capacity which would have been available in absence of reneging by plant $r \in \mathcal{R}_t$, the set of plants which reneged. By construction, in absence of strategic reaction from competitors, $\widehat{RD}_t^\star$ and $\overline{RD}_t$ should be statistically equivalent.

The direct effects of reneging on market outcomes are measured using an alternative counterfactual residual demand functions accounting for reneging but assuming no strategic reaction. It is defined as $\widetilde{RD}_t^\star = D_t - (\widehat{RS}_t^\star - \sum_{r \in \mathcal{R}_t} \hat{S}_t^r)$, where $\hat{S}_t^r$ is a prediction of the supply functions of PPA plant r in normal conditions. Substracting it from $\widehat{RS}_t^\star$ hence yields the market supply net of the PPA plant under outage under

[45] As mentioned earlier, 74% of PPA capacity is offered at \$0/MWh.

normal conditions, that is in absence of strategic reactions. Note that all those residual demand functions are modified ex-post to account for the exogenous net import functions and demand-response functions used in Ayres (2014).

Our objective is to evaluate the causal effects of reneging on market outcomes, that is price and output deviations. The equilibrium condition, given by

$$\widehat{S}_t^{\star}(\hat{P}_t) = \widehat{RD}_t^{\star}(\hat{P}_t), \tag{14}$$

yields the counterfactual price $\hat{P}_t$ as well as the corresponding firm's output $\widehat{Q}_t^{\star} = \widehat{S^{\star}}_t(\hat{P}_t)$. The output change is defined as $\widehat{\Delta Q}_t = Q_t - \widehat{Q}_t^{\star}$ and the price impact is $\widehat{\Delta P}_t = P_t - \widehat{P}_t$. If the predictive model performs well, those values should be statistically close to zero except if reneging affects market outcomes. This approach has the desirable feature to account for the strategic reactions to reneging of competitors, in addition to the firm's own strategic reaction.

We illustrate the different counterfactual predictions in Figure 1 for February 16, 2011. The observed equilibrium "OE" is obtained from the observed functions $(S_t^{\dagger}, RD^{\dagger})$. The MSA's methodology in Ayres (2014) consists in calculating the counterfactual outcome "CE 1" from $(S_t^{\dagger}, \overline{RD}_t)$.[46] Our approach consists in predicting $(S_t^{\star}, RD_t^{\star})$ to obtain the counterfactual equilibrium "CE 2" which would have prevailed in absence of reneging. Finally, the direct effect of reneging, assuming firms did not modify their strategies upon observing the outage, is given by the intermediate outcome "CE 3" obtained from $(S_t^{\star}, \widetilde{RD}^{\star})$.

[Figure 1]

This outage was declared on February 14, 2010 (AUC, 2015), so all firms had sufficient time to modify their spot strategies accounting for the outage information.

[46] The methodology includes additional refinements with relatively small effects in our setting, as discussed later.

This example illustrates several facts. First, the comparison of $\overline{RD}_t$ and $RD_t^\star$ reveals that competitors have engaged in economic withholding during the outages. They have thus also contributed to the price impacts. Second, the comparison of $S_t^\dagger$ and $S_t^\star$ shows that neglecting the firm's own strategic reaction can lead to vastly underestimate the price impact, whatever the counterfactual residual function used. These results are in line with Frayer (2014) who provides some evidence of the coincidental economic withholding from both TransAlta and ATCO during this event. Third, the intermediate outcome "CE 3" suggests that most of the price impact in this case resulted from the outage itself and not the strategic reactions of the firms. Firms probably engaged in this behaviour to increase the likelihood of receiving large prices.

Identification. The identification of causal estimates relies on the assumption that the treatment selection conditionally on covariates is as good as random. This assumption holds as long as, conditional on the covariates, the strategic outage decision depends only on random factors independent of market conditions, such as having a "good excuse" to substantiate the need for urgent maintenance.[47]

Our approach can be summarized as comparing "similar days" in terms of weather, wind, demand, import and export capacities, natural gas price, time of the day, day of the week, month, and the capacity availability of each single generator in the system. Those identification conditions are similar to those used in the (propensity score) matching literature. The control variables are selected in light of our theoretical model. It showed that the principal factors affecting the profitability of reneging are related to expectations about demand, wind, and the residual demand's elasticity. We thus claim that the identifying restriction holds because: 1) all of these factors can be controlled for *to some extent* using observable variables, and 2) the counterfactual predictions

[47]The regulatory investigation revealed that each event was initiated by a plant operator reporting a (non-urgent) technical issue to the trading department (AUC, 2015).

obtained under this assumption are consistent with our theoretical results. Note that we cannot condition directly upon the realized strategies of rivals since they are endogenous, which is why they are separately predicted.

However, our identifying assumption is subject to some limitations. A bias may arise if the data used to estimate the model, the "control group", differs in systematic ways from the data when reneging occurs, the "treatment group", because of unobservable factors.[48] For instance, if reneging occurs partly because some particular rival generator is in maintenance but there is no similar observation in the control group where this generator is unavailable, then we might lack information about supply strategies in this circumstance and the counterfactual predictions would be biased. It is also possible that the firm's decision to renege depends on market dynamics, such as recent rival bidding behaviours. For instance, Brown, Eckert and Lin (2018) argue that firms in Alberta may be utilizing bidding patterns to communicate with their rivals to increase market prices. If the occurrence of such collusive behaviours is correlated with that of strategic reneging, our counterfactual predictions would suffer from a selection bias.[49] Bearing these limits in mind, we now present the rest of our methodology.

Estimation. Let us consider the following functional linear model

$$S_t(p) = \beta_K(p)'K_t + \beta_Z(p)'Z_t + \alpha(p)'X_t + u_t(p), \tag{15}$$

defined for all p, where $S_t(p)$ is the firm's supply as a function of the price p, K_t is the vector of available capacity of each generator $s \in \{1, ..., 77\}$, and Z_t is a set of 212 predictors including market demand, wind production from ENMAX, SUNCOR,

[48] Although instrumental variables might provide a solution to this limitation, accommodating for an endogenous treatment in our functional framework with variable selection is beyond the scope of this paper.

[49] Remark that such a bias might change the signs of supply shifts and yield results that could potentially contradict our theory.

TransAlta and the fringe, natural gas prices, total import and export capacities, and weather controls. Weather controls include heating and cooling degrees with respect to 10°C for Calgary, Edmonton, Vancouver and Saskatoon, in addition to a collection of 194 variables from weather stations: 52 temperature variables, 46 dew point variables, 46 humidity variables, 33 wind speed variables, and 17 wind angles variables. The variable X_t is a set of time dummies for hours of the day, days of the week, and weeks. u_t is a functional error term.

Although equilibrium strategies are best-response to each other, our objective is to identify the best exogenous (or more precisely *pre-determined*) predictors of firm-level strategies. Doing so allows to predict equilibrium strategies without solving for an equilibrium, because they will depend on each other through the predictors only. The model does not condition directly upon the strategies of rivals. However, the specification includes the hourly capacity availability of every single generator in Alberta, irrespective of their ownership or control, unless it does not vary throughout our sample.[50] These variables are used to control for the expected residual demand's elasticity and the fact that TransAlta may have based its reneging decisions on some particular rival generator's availability.

The model parameters are functions defined over the price interval, and thus are infinite-dimensional. To reduce the dimensionality,[51] we estimate the multivariate model given by

$$\boldsymbol{S_t} = \boldsymbol{\beta}'_{\boldsymbol{K}}\boldsymbol{K_t} + \boldsymbol{\beta}'_{\boldsymbol{Z}}\boldsymbol{Z_t} + \boldsymbol{\alpha}'\boldsymbol{X_t} + \boldsymbol{u_t}, \tag{16}$$

where the variables are evaluated over an evenly-spaced grid of prices $\{p_1, p_2, ..., p_L\}$ and stacked into vectors of length $L = 52$, denoted by bold variables. For example,

[50] During hours with reneging, we predict the counterfactual strategies by setting the available capacity of the unavailable plant s to its value in the hour preceding any reneging.

[51] The estimation of the functional model in (15) can be done using the approach of Benatia, Carrasco and Florens (2017) although it would not allow for variable selection.

$\boldsymbol{S_t} = \begin{pmatrix} S_t(p_1) & S_t(p_2) & ... & S_t(p_L) \end{pmatrix}'$ is a vector of supply quantities evaluated over the price grid. Vectors for variables that do not depend on p in (15) consist of repeated values. $\boldsymbol{u_t}$ is an iid multivariate gaussian error term. The exact same model is applied to the residual supply $RS(p) = \sum_{j \neq TA} S_j(p)$ instead of $S(p)$, which yields the estimate of interest $\widehat{RD}_t(p) = D_t - \widehat{RS}_t(p)$.

The models are trained and evaluated as follows. We train predictive models of strategic bidding using the observations outside of those events. We carry the estimation separately for the samples of off-peak (21:00 to 07:00) and peak hours (07:00 to 21:00). All hourly observations where reneging occurred during the same day are assigned to a "reneging set". This consists of the treatment group, whereas the remaining sample is considered as the control group. We split those remaining observations into a training set and a testing set. The training set is used to estimate the model whereas the testing set is used to evaluate its predictive power. Sample splitting is done randomly so that the training sample has roughly 70% of observations.

The model is estimated on the training set of observations with the multivariate extension of the lasso developed by Simon, Friedman and Hastie (2013).[52] By design, the lasso selects variables that best predict the outcome of interest and shrinks the others to zero. The lasso is a form of penalized regression useful for model selection. In our setting, it is difficult to know what drives the firm's strategy. At the same time, we want to prevent overfitting issues caused by the inclusion of too many variables. The model parsimony depends crucially on the chosen value of a tuning parameter λ. We opt for using 20-fold cross-validation and select the value of λ, often referred to as λ_{1se}, that gives the most regularized model such that the cross-validated error is within one standard error of the minimum average mean-squared-errors.

[52] More specifically, we use the glmnet package. We also tried using an elastic net regression, that is the combination of $\mathbb{L}_1$ (lasso) and $\mathbb{L}_2$ (ridge) penalties of the parameters, and a neural network. The results were slightly worse in terms of RMSE on the testing set and are thus not reproduced here.

Finally, the predicted functions obtained from model (16) are finite-dimensional vectors that are not restricted to be monotone, unlike supply functions. We recover monotone function for each estimate by imposing an ex-post monotone constraint.

Inference. Inference boils down to testing the null hypothesis

$$H_0 : \widehat{\Delta S}_t(p) = 0, \quad \forall p. \tag{17}$$

The test statistics are derived from weighted Chi-square distributions, with weights that depend on the eigenvalues of the asymptotic covariance operator of the functions $\widehat{\Delta S}_t(\cdot)$. Because these distributions are not symmetric, the standard errors are not appropriate to assess statistical significance. It would be possible to use a t-test, but that would only provide a pointwise evaluation of statistical significance. In contrast, we choose to use a (uniform) test which evaluates the significance of the entire functions. We compute p-values using an asymptotic approximation and a parametric bootstrap. The bootstrap is especially relevant to conduct inference on price impacts estimated from these functional predictions. The formal description of our method is given in Appendix C.

Model evaluation. Table 6 shows the main summary statistics of model performance for S and RS for peak hours[53] in the training, testing and reneging set, as well as coverage probabilities for prices and outputs' confidence intervals. The last column reports the associated statistics for $\widehat{RS}$ evaluated against the constructed counterfactual $\overline{RS}$ which assumes no outage and no strategic response.

The model performs well for both S and RS. The supply prediction exhibits a mean integrated absolute bias of 22.9 MW on the testing set, which corresponds to a mean integrated relative absolute error of 2.7%. The root-mean-integrated-squared-

[53]Results are similar for off-peak hours (Table B2 Appendix B).

error (RMISE) is also within the same order of magnitude for both the training and testing sets, meaning that overfitting is not a concern. Substantially larger biases and RMISE are observed for the reneging set.

Inference also performs correctly on the testing set.[54] The rejection rates for the functional test defined in (17) are reasonably close to the nominal size of 5% for both the asymptotic approximation and the bootstrap. The last rows report the coverage probabilities for estimated prices and outputs derived from the pair of functions $(\widehat{S}, RS)$, that is using the observed residual supply, and $(\widehat{S}, \widehat{RS})$, i.e. using the predicted residual supply. Those bootstrapped confidence intervals are reasonably close to the nominal 95% for the testing set.

The results for the reneging set yield important insights. As expected, the predictions $(\widehat{S}, \widehat{RS})$ differ significantly from their observed values. We find that observed supply strategies differ significantly from their predicted counterfactual in about 14.5% of reneging hours. Since $\overline{RS}$ does not account neither for the strategic reaction of competitors to the outages, nor for bids above zero prices at PPA plants, while $\widehat{RS}$ does, their difference provides evidence that the regulator's constructed residual demand may be biased. We find that it is the case in 46-47% of reneging hours. Finally, coverage probabilities for equilibrium outcomes indicate that counterfactual prices and outputs differ significantly from observed ones.

[Table 6]

Strategic reactions and counterfactual equilibria. The supply and residual demand predictions are used to compute counterfactual market outcomes for each event, which can then be investigated as 11 separate case studies. Our objective is to evaluate the impacts of market manipulations. We consider two simple scenarios. First, the outages of the first day of each event could have been delayed until after 21:00 the

[54]We do not compute these statistics for the training set to reduce computation time.

same day. Follow-up outages like on December 14 are assumed unavoidable. Second, all outages could have been delayed to the next planned maintenance, during which they would have had no impact. In scenario 1, only the first hours of the outages could have been avoided, whereas all outage hours could have been avoided in scenario 2.[55] Recall that the experts established that it would have been feasible to move the outages to the next week-end or the next planned outages (Heath, 2014; Eisenhart, 2014), which provide more support for scenario 2 than scenario 1.

We first illustrate the hourly results for six hours in Figures 2a to 2f. Observed supply and residual demand functions are shown by the plain lines and counterfactuals are represented in the same way as in Figure 1. We also display the 95% confidence intervals of the counterfactual supply and residual demand functions, as well as the 95% highest density region of counterfactual equilibrium outcomes.[56]

[Figure 2]

For November 19, November 23, and April 12, i.e. Figure 2a, 2b and 2f, we find that TransAlta's supply strategy was increased compared to the counterfactual, which allowed the firm to increase its equilibrium output. In addition, the large difference between $RD^{\dagger}$ and $\widetilde{RD}$ reveals that some rival suppliers have engaged in economic withholding. This result is in line with Frayer (2014) who shows the coincidental economic withholding of 400 MW by TransCanada on November 19, 2010 in the same hour. For December 13 (Figure 2c) and January 15 (Figure 2e), we find no significant supply or residual demand difference. Finally, the results for February 16 illustrate the negative supply shifts shown in Proposition 6. Figure 2d shows that TransAlta and some of its competitors economically withheld capacity in complement to the PPA outage. The 95% highest density region, although large, reveals that a price above

[55] Ayres (2014) study four scenarios based on these two extremes.

[56] The bootstrapped distribution is used to estimate highest density regions and construct a confidence set for equilibrium outcomes $(\hat{P}_t^{\star}, \hat{Q}_t^{\star})$ (Hyndman, 1996).

$800 would have been unlikely in absence of reneging. Note that in all of the events, it appears that TransAlta did declare the outages more than 2 hours before production. The shortest notice appears to be for December 13 when an outage at Sun 2 to be started at 16:00 was declared at 13:51 (AUC, 2015). Therefore, all rivals were able to modify their bids accounting for the outage information.

Figures 3 and 4 report the average output (for TransAlta) and price impacts separately for the first hours of each event (scenario 1), and all hours of each event (scenario 2). We also show the values obtained using the methodology of the MSA in Ayres (2014) for comparison. It appears that our method yields on average larger price and quantity impacts than those estimated by the regulator. The average output of TransAlta is found to have increased significantly in most events.

[Figure 3]

Price impacts are consistently large and in general higher during the first hours of the outages. As regards the additional events, we find no evidence of price impacts for November 24, November 26, and January 21, but significant effects for November 30, January 15, April 12, and August 12. These estimates suggest that the regulator failed to consider all manipulation events.

[Figure 4]

The estimated strategy shifts can be summarized by focusing on the integrated difference between the observed function and its prediction, $\widehat{\Delta S}_t = \int_{\underline{p}}^{\overline{p}} \left(S_t(p) - \widehat{S}_t^{\star}(p) \right) dp$ and $\widehat{\Delta RD}_t = \int_{\underline{p}}^{\overline{p}} \left(\overline{RD}_t(p) - \widehat{RD}_t^{\star}(p) \right) dp$ possibly over different price intervals. This provides information about whether supply offers have been modified. We report the average of these statistics for each event in Figure 5 for all hours of the outages, along with 95% confidence intervals. We find that not only TransAlta's supply strategy was significantly modified during the events, its residual demand often shifted to the right by more than the reneged quantity, hence the positive average estimates.

[Figure 5]

Testing the model's predictions. Our theoretical model has four testable implications: 1) the magnitude of strategy shifts are positively related to the elasticity of residual demand; 2) price impacts are negatively related to the elasticity of residual demand; 3) output impacts are positively related to the elasticity of residual demand; and, 4) negative supply shifts are profitable only to benefit from a large discontinuity jump in the residual demand function.

To test the first three predictions, we regress $\widehat{\Delta S}_t$, $\widehat{\Delta P}_t$ and $\widehat{\Delta Q}_t$ onto the slope of residual demand functions, the outage capacity, and time fixed-effects for hours of the day and days of the week. An increase in the slope implies a less elastic function (more vertical inverse function) hence smaller strategy shifts, lower quantity cuts, and larger price jumps. The first three columns in Table 7 show that the empirical results are in line with those theoretical predictions during the main events (all hours), and all eight events where a price impact was found, as shown in Figure 4. Note that the supply strategy is shifted to the right by around 9% of the outage size (in MW), which roughly corresponds to TransAlta's market share.

The last column of Table 7 shows regression results of $\mathbb{1}_{\widehat{\Delta S}_t<0}$, a dummy equal to 1 when the (integrated) supply shift is negative, onto the slope of RD, outage capacity, and the same time fixed-effects. As expected, negative shifts strongly coincide with less elastic residual demand functions. As a falsification test, we run the same regressions using the testing set and find that the coefficients are of lower magnitude and of opposite signs. Note that outage size is omitted because it is always zero.[57]

[Table 7]

[57] It is not surprising that residual demand can be a significant predictor of the price residuals as it is not used in our prediction model.

3.4 Manipulation Gains and Procurement Costs

The gains from manipulations. The firm-level hourly gross gains from reneging are defined as

$$\widehat{\Delta\Pi}_t = P_t Q_t - \widehat{P}_t \widehat{Q}^\star_t. \tag{18}$$

Those gains result directly from reneging, i.e. the outage-induced displacement of the residual demand function, but also indirectly through the firm's supply strategy shift and the reactions of its competitors.

We isolate the direct effect of reneging on revenues, using the counterfactual residual demand $\widetilde{RD}^\star_t$ defined earlier. The counterfactual outcome $(\widetilde{P}_t, \widetilde{Q}^\star_t)$ is determined by the condition $\widehat{S}^\star_t(\widetilde{P}_t) = \widetilde{RD}^\star_t(\widetilde{P}_t)$. The direct gains from reneging are hence given by $\widetilde{P}_t\widetilde{Q}^\star_t - \widehat{P}_t\widehat{Q}^\star_t$, whereas indirect gains are $P_tQ_t - \widetilde{P}_t\widetilde{Q}^\star_t$.

Table 8 reports the gross gains of reneging separately for the first hours (until 21:00 the first day), and all hours, aggregated by event. The firm's total gains from manipulations are evaluated at \$13 million for the first hours (+190%), and \$67 million when accounting for all outage hours (+220%), which correspond to a three-fold increase in gross market revenues. Although the direct gains from reneging make the bulk of those revenues, respectively 63% and 83%, the strategic reactions generated most of the revenues in some events, like on November 19 and November 23. This result confirms that strategic reneging can create or enhance market power.

In support of this idea, we compare our results to the estimates obtained using the MSA's methodology. It appears that neglecting strategic effects may lead to greatly underestimating (-50% on February 16) or overestimating (+34% on August 12) market impacts. Focusing on the four main events, we find that the bias is -27% for the first hours, and -11% when considering all hours. However, the bias shrinks to only -4% when considering all hours and all events.

[Table 8]

These estimates abstract from potential cost variations related to output changes, financial forward contracts, and outage costs. Cost changes, though probably small, could be accounted for using the estimates from Brown and Olmstead (2017). However, forward contracts can substantially reduce those gains if a large share of the firm's output is committed to being supplied at the forward price. Data on physical and financial forward contracts are difficult to obtain, so we must neglect this aspect.[58] Outage costs consist of the foregone revenues from reneged commitments and penalty charges, which could be calculated if one had detailed information on the contractual arrangements. However, the firm would have had to shut down the plant for maintenance anyway, although at a period to avoid large market impacts. The firm would have incurred some costs anyway due to the design of availability incentive payments.

Changes in procurement costs. Short-run demand being inelastic, the only impact of strategic reneging on total welfare results from the inefficiencies on the supply-side. More expensive production units are used instead of cheap coal-fired plants under outage, which undermines the system efficiency and brings up prices. However, this cost inefficiency is likely to be small, because reneging affects only a tiny fraction of the total supply. We hence choose to focus only on the "redistributive" impacts of the outages, which corresponds to the transfer from buyers to sellers given by $\widehat{T}_t = \left(P_t - \widehat{P}_t\right) D_t$. It corresponds to a transfer from retailers/consumers to producers in absence of financial forward contracts. In their presence, the total is unchanged but gains and losses are distributed differently. For example, *Capital Power*, the supplier whose complaint initiated the regulatory investigation, claims to have made considerable losses because of its net buying position in the spot market during several of the events.

The direct effect of reneging on this transfer is defined by $\left(\widetilde{P}_t - \widehat{P}_t\right) D_t$. The re-

[58]Hortaçsu and Puller (2008) propose a method to estimate forward positions from marginal cost estimates and bid functions.

maining part of the transfer, $\left(P_t - \widetilde{P}_t\right) D_t$, is generated by the strategic responses to reneging. Table 9 reports the transfers for each event, separately for the first hours and all hours. The manipulations caused total power procurement costs to increase by \$115 million over the first hours of all events, and \$596 million when considering all hours. This corresponds to a three-fold increase in procurement costs during these days, or between 3% to 17% of the annual procurement costs between November 2010 and October 2011. Therefore, the total increase in procurement costs can greatly vary with the counterfactual outage scenario. The expert reports, however, provide more support for the largest figure.

The direct effects of reneging consist of between 64% and 82% of total cost increases, albeit the strategic component is also sizable in some cases. Note that the estimates obtained following the MSA's methodology are biased in most cases. Considering only the main four events, there are negative biases of about 30% for the first hours and 12% for all hours.

[Table 9]

It turns out that neglecting strategic effects can lead to vastly underestimated market impacts, not only by failing to account for a large share of the impacts, but also by using the wrong reference point.[59] We evaluate TransAlta's undue profits from manipulations between \$13 million and \$67 million, a figure that is comparable to the \$56 million settlement paid by the manipulator. However, this settlement covers less than 10% of our largest estimate of increases in procurement costs. The remaining hundreds of millions, which consist of windfall revenues to suppliers who benefited from the manipulation, will never be recovered by ratepayers.

[59] We evaluate market impacts by calculating the effect of moving from the supply-residual demand pair without reneging $(S_t^\star, RD_t^\star)$, to the pair with reneging $(S_t^\dagger, RD_t^\dagger)$, whereas neglecting strategic effects leads to evaluate the effect of moving from $(S_t^\dagger, RD_t^\dagger - R)$, with R being the reneged output, to $(S_t^\dagger, RD_t^\dagger)$.

As the theory shows, the ability to strategically renege has impacts on futures contract prices, and in turn on spot prices through equilibrium effects. These impacts can be difficult to quantify empirically, and even more so due to the inherent lack of data on financial forward contracts. Our model predicts that forward prices must have increased in response to expectations of higher spot prices caused by the manipulations. Yet, it shows that part of the price discrepancy created by the firm's conduct may remain in equilibrium. A spot price premium might even have prevailed in equilibrium over the long run, had the firm been able to continue this strategy. Evidence shows that TransAlta's traders noticed that (month-ahead) forward prices for March 2011 increased by 30% above expectations, reflecting the impacts of the strategic outages (AUC, 2015). Those overvalued forward contracts were seen as another trading opportunity. The firm planned to take a net buying position on the spot market, then reverse its outage and bidding strategies to maintain spot prices as low as possible. In absence of regulatory intervention, the firm would have optimized its informational advantage about forced outages by alternating these two strategies over time.

Even though we account for strategic behaviours in the spot market, our analysis neglects the general equilibrium effects, such as the consequences for forward markets. Our figures should hence be seen as a partial picture of the harm resulting from reneging.

4 Conclusion

We study incentives to manipulate sequential markets arising from imperfect commitment. We show how a supplier with market power would modify its supply strategy upon anticipating a potentially profitable deviation from its commitments. Our model provides guidance for the detection of potential misconduct related to strategic reneging. In an application to Alberta's electricity market, we confirm our theoretical predictions and estimate that this commitment problem had harmful welfare consequences for consumers, some of which were not detected by the regulator. Albeit long-term contracts were primarily implemented in the province to mitigate potential market power issues, they created powerful incentives to manipulate markets. This downside of sequential markets that we evidence constitutes a serious issue beyond this specific case.

Our analysis shows that strategic reneging can take various forms. The findings suggest that the firm strategically curtailed wind power during episodes of large demand, in addition to timing forced outages at coal-fired plants. This illustrates how long-term renewable contracts, like feed-in tariffs, provide horizontally-diversified firms with a free channel for undue profits. The extensive use of long-term contracts without delivery obligations, as means to support the development of intermittent renewables, will lead to similar issues if contracts are concentrated within the hands of otherwise large suppliers. This stresses the importance of facilitating renewable investment from entrants rather than incumbent firms, and of the centralization of wind dispatch by the system operators.

We argue that these issues can occur beyond electricity markets. The method outlined in this research is a step toward the development of new tools for the detection and evaluation of market manipulations. It also illustrates how theoretical models and machine learning methods can complement each other for regulatory purposes. We claim that, with all its limits, the implications of this research should extend to all markets that are somehow interrelated (not only through time) and subject to imperfect commitment.

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Tables and Figures

Table 1: Alberta market and firm characteristics

	Market shares (%)	Capacity (%)
TransCanada (TC)	20.9	4.2
ENMAX (EN)	18.3	6.5
Capital Power (CP)	11.8	11.8
TransAlta (TA)	10.4	36.7
ATCO (AT)	8.2	16.2
Fringe	30.4	24.5

This table shows market shares of capacity for which a firm can submit offer bids versus capacity ownership by firm (%). Market shares are calculated as average share of available capacity over total capacity. Capacity shares are based on ownership rather than offer controls.

Table 2: Timing of strategic outage events

	Start	End	Facility	Mean Outage	Buyer
	Main Events (investigated by the regulator)				
Event 1	Nov 19, 2010 16:00	Nov 22, 2010 03:00	SD 5	-280 MW	CP
Event 2	Nov 23, 2010 09:00	Nov 24, 2010 00:00	SD 2	-125 MW	TC
Event 3	Dec 13, 2010 16:00	Dec 16, 2010 18:00	SD 2	-288 MW	TC
	Dec 13, 2010 16:00	Dec 15, 2010 03:00	KH 1	-385 MW	EN
	Dec 14, 2010 17:00	Dec 16, 2010 23:00	SD 6	-401 MW	CP
Event 4	Feb 16, 2011 17:00	Feb 18, 2011 21:00	KH 2	-387 MW	EN
	Additional Events (from the witness statements)				
Event 5	Nov 24, 2010 13:00	Nov 25, 2010 17:00	SD 5	-175 MW	CP
Event 6	Nov 26, 2010 15:00	Nov 29, 2010 14:00	SD 3	-325 MW	TC
Event 7	Nov 30, 2010 14:00	Dec 03, 2010 07:00	KH 2	-387 MW	EN
Event 8	Jan 15, 2011 09:00	Jan 18, 2011 11:00	KH 2	-387 MW	EN
	Jan 17, 2011 16:00	Jan 18, 2011 14:00	KH 1	-387 MW	EN
Event 9	Jan 21, 2011 13:00	Jan 25, 2011 06:00	SD 4	-406 MW	TC
	Jan 25, 2011 15:00	Jan 27, 2011 16:00	SD 5	-406 MW	CP
	Jan 27, 2011 07:00	Jan 27, 2011 10:00	KH 2	-387 MW	EN
Event 10	Apr 12, 2011 13:00	Apr 15, 2011 10:00	SD 5	-406 MW	CP
	Apr 14, 2011 18:00	Apr 18, 2011 21:00	SD 4	- 406 MW	TC
Event 11	Aug 12, 2011 16:00	Aug 19, 2011 23:00	SD 5	-406 MW	CP
	Aug 14, 2011 22:00	Aug 19, 2011 23:00	SD 4	-406 MW	TC

Notes: This table provides a summary of the timing of outage events investigated by the regulator, as well as outage events pointed out by PPA buyers. Most outages/derates lasted about two days. Timing and mean outage are only indicative as plants gradually decrease/increase output, possibly over a few hours, to be fully offline/online.

Table 3: Summary statistics

	Training set		Testing set		Events		Add. Events	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Off-Peak (21:00 to 07:00)								
Output (GWh)	6.96	0.58	6.93	0.56	7.78	0.41	7.41	0.50
Price (CAD)	31.8	43.1	30.4	34.3	66.6	143.9	40.7	60.3
Av. Capacity (GW)	8.35	0.49	8.32	0.48	8.91	0.43	8.42	0.53
Mean Bid TA (MW)	822	150	818	148	739	35	764	63
Mean Bid RS (MW)	6766	457	6748	447	7266	410	6876	517
Wind TA (MWh)	117	115	119	116	86	143	140	137
Wind (MWh)	197	170	198	171	135	205	220	193
NG Price (CAD)	3.9	1.0	3.9	0.9	3.7	0.2	3.7	0.3
Temp Calgary (°C)	1.7	10.7	2.5	10.3	-14.7	8.7	-2.4	10.7
Observations	7049		2820		110		340	
Peak (07:00 to 21:00)								
Output (GWh)	7.82	0.55	7.81	0.55	8.68	0.30	8.26	0.47
Price (CAD)	71.3	129.6	72.1	131.8	317.3	330.6	124.7	202.0
Av. Capacity (GW)	8.45	0.47	8.43	0.48	8.96	0.43	8.56	0.54
Mean Bid TA (MW)	925	158	922	160	869	46	862	61
Mean Bid RS (MW)	7018	443	7004	449	7405	420	7118	530
Wind TA (MWh)	120	121	119	121	81	141	159	157
Wind (MWh)	189	176	187	177	129	210	237	217
NG Price (CAD)	3.9	1.0	3.9	1.0	3.7	0.2	3.7	0.3
Temp Calgary (°C)	5.6	12.0	6.0	11.8	-13.9	8.9	0.8	12.1
Observations	9890		3918		154		476	

Notes: This table shows descriptive statistics (mean and standard deviation) of the main variables. Av. Capacity is the total available hourly capacity. Mean Bid is the average quantity offered across all prices of the price grid. TA refers to TransAlta. RS refers to the residual supply net of TA.

Table 4: Strategic timing of forced outages

	(1)	(2)	(3)	(4)
Demand (GWh)	$0.004^{\star}$	$0.040^{\star\star}$	0.01	-0.03
	(0.002)	(0.017)	(0.007)	(0.031)
Wind (GWh)	-0.006	$-0.068^{\star\star}$	0.01	-0.07
	(0.004)	(0.035)	(0.012)	(0.070)
Observations	7292	7292	17465	17465
R^2	0.01	0.09	0.01	0.05

Notes: This table shows the estimation results of equation (11). The dependent variable is a binary variable equal to 1 in the first four or all hours during outage events. The first two columns focus on the suspicious outages after November 2010, whereas the last two focus on all outages before. All regressions include fixed-effects for hours of the day, days of the week, months and years. Newey-West robust standard errors are reported in parentheses.

Table 5: Strategic wind curtailment

	Wind TA	Wind TA	Wind EN	Wind SC
After Nov 1, 2010	$-3.65^{\star}$			
	(1.95)			
Main events		$-10.22^{\star\star\star}$	1.42	-0.10
		(3.25)	(2.36)	(1.18)
Add. Events		-3.53	-1.25	-0.09
		(3.06)	(1.27)	(0.52)
Observations	24757	24757	24757	24757
R^2	0.87	0.87	0.85	0.83

Notes: This table shows the estimation results of equation (12). The dependent variable is TransAlta's aggregate wind power production in MWh (columns 1 & 2) or ENMAX's (column 3) or SUNCOR's (column 4). All regressions include fixed-effects for hours of the day, days of the week, months, and years. We also control for 4 wind speed measures from nearby weather stations, and all rivals' wind power plant output. Newey-West robust standard errors are reported in parentheses.

Table 6: Model performance (Peak hours)

	Training set		Testing set		Reneging set		
n	9890		3918		630		
Parameters	320						
	S	RS	S	RS	S	RS	$\overline{RS}$
Mean Int. Bias	1.7	2.8	2.7	2.6	−0.5	−357.7	4.0
Mean Int. Abs. Bias	22.7	54.7	22.9	55.6	28.3	381.8	121.7
Mean Int. Rel. Abs. Bias	2.5%	0.8%	2.6%	0.8%	3.3%	5.5%	1.7%
RMISE	29.4	81.2	29.6	83.1	38.7	470.6	171.3
Rejection Rate (Imhof) H_0	–	–	0.062	0.064	0.144	1	0.460
Rejection Rate (BS) H_0	–	–	0.060	0.069	0.146	1	0.471
Zero parameters	95	91					
λ_{CV}	0.004	0.005					
Coverage probabilities	RS	$\hat{RS}$	RS	$\hat{RS}$	RS	$\hat{RS}$	$\overline{RS}$
Price	–	–	0.92	0.93	0.75	0.33	0.16
Output	–	–	0.92	0.91	0.73	0.60	0.62

Notes: This table shows statistics of model performance separately for the training set, testing set and reneging set. The reneging set includes all hours for days when reneging occurred. The statistics include Mean Integrated Bias, Absolute Bias, Relative Absolute Bias, the root-mean-integrated-squared-errors (RMISE), rejection rates using the asymptotic distribution (Imhof) and parametric bootstrap (BS). Zero parameters is the number of parameters set to zero by the algorithm (on average across the 52 price values). Inference for functions is described in Appendix C.

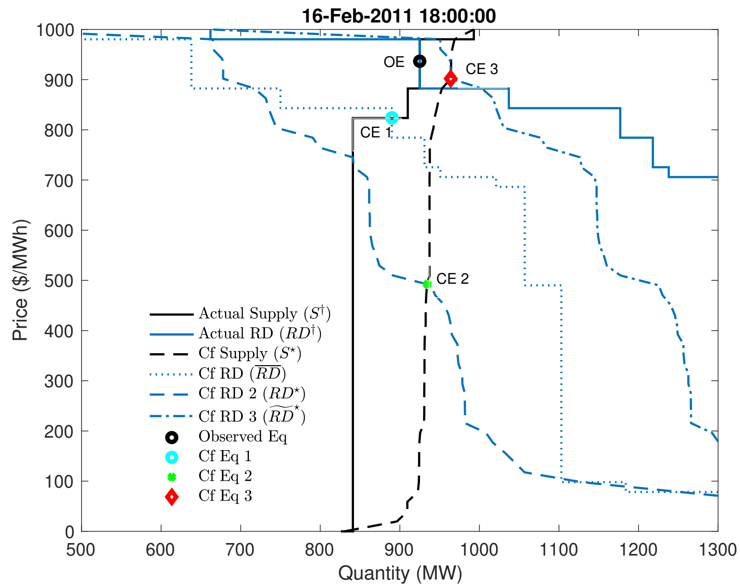
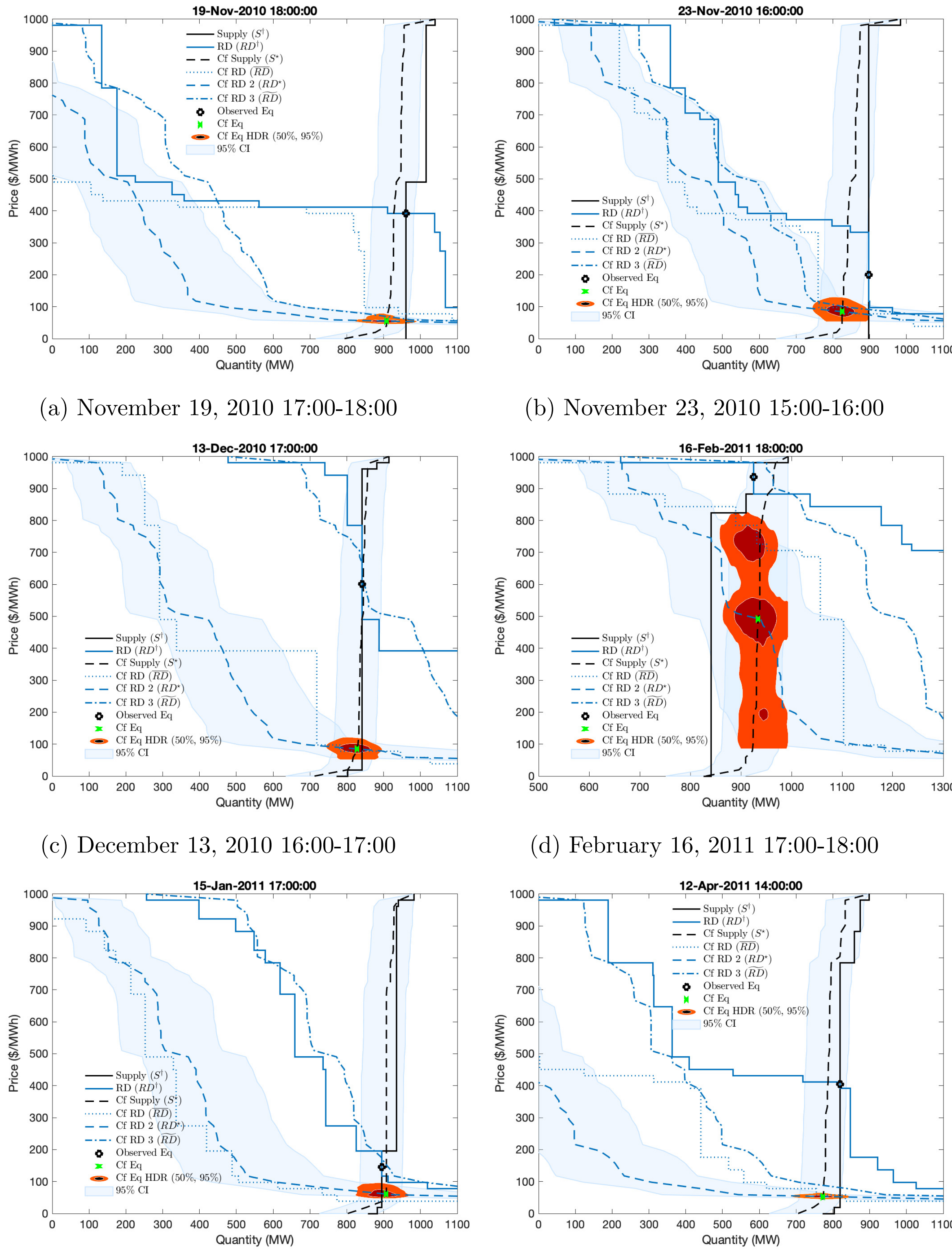


Figure 1: February 16, 2011 17:00-18:00



(a) November 19, 2010 17:00-18:00

(b) November 23, 2010 15:00-16:00

(c) December 13, 2010 16:00-17:00

(d) February 16, 2011 17:00-18:00

(e) January 15, 2011 16:00-17:00

(f) April 12, 2011 13:00-14:00

Figure 2: Illustrative counterfactual predictions

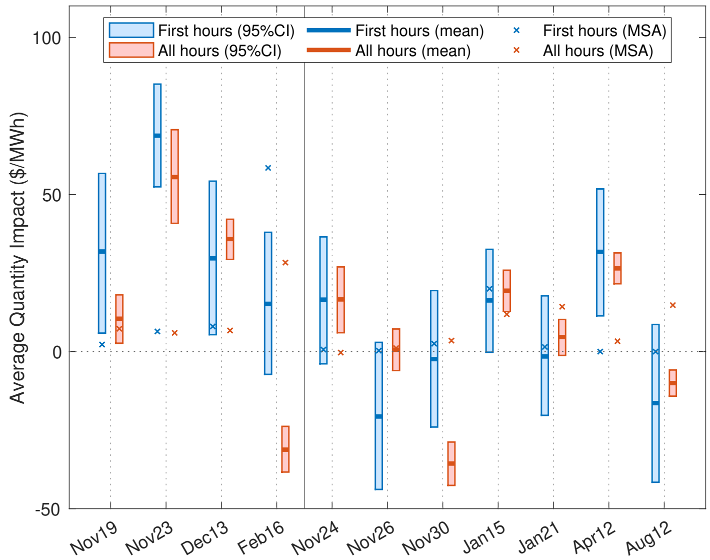


Figure 3: Average quantity impacts

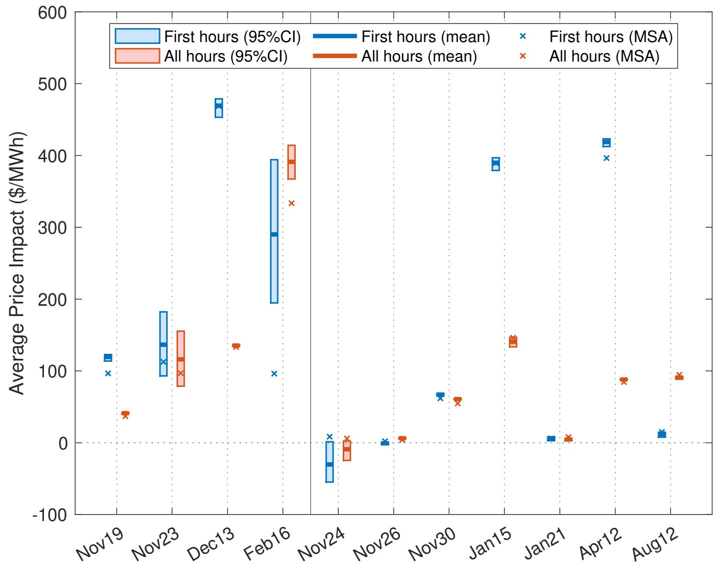


Figure 4: Average price impacts

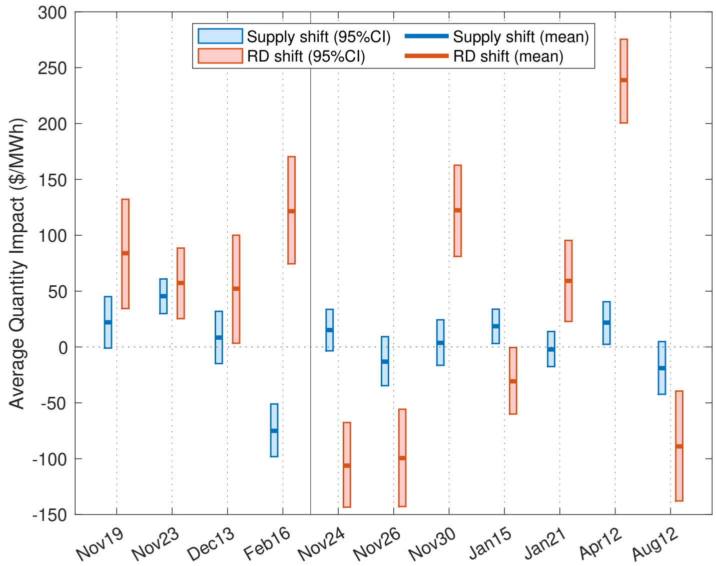


Figure 5: Average bid function impacts (all hours)

Table 7: Strategy shifts, market impacts, and residual demand

		$\widehat{\Delta S}$	$\widehat{\Delta Q}$	$\widehat{\Delta P}$	$\mathbb{1}_{\widehat{\Delta S}<0}$
Main events	RD slope	$-92.53^{\star\star\star}$	$-54.50^{\star\star\star}$	$276.52^{\star\star\star}$	$0.91^{\star\star\star}$
		(11.89)	(15.83)	(76.23)	(0.16)
	Outage capacity	$0.09^{\star\star\star}$	$0.09^{\star\star\star}$	-0.09	$-0.00^{\star\star\star}$
		(0.02)	(0.02)	(0.10)	(0.00)
	Observations	200	200	200	200
	R^2	0.58	0.54	0.52	0.52
All events	RD slope	$-43.00^{\star\star\star}$	$-33.91^{\star\star}$	$141.52^{\star\star}$	$0.32^{\star\star}$
		(12.93)	(13.77)	(67.10)	(0.14)
	Outage capacity	0.04	$0.04^{\star}$	-0.05	-0.00
		(0.02)	(0.03)	(0.04)	(0.00)
	Observations	643	643	643	643
	R^2	0.14	0.08	0.30	0.06
Testing	RD slope	5.76	-1.52	$-29.43^{\star\star\star}$	$-0.12^{\star}$
		(5.04)	(4.62)	(9.10)	(0.07)
	Observations	6738	6738	6738	6738
	R^2	0.01	0.01	0.02	0.01

Notes: This table shows regression results where the dependent variable is supply strategy shifts (column 1), output impacts (column 2), price impacts (column 3), and a dummy equal to one if strategy shifts are negative (column 4). Newey-West standard errors are reported in parentheses.

Table 8: Profitability of the manipulations

	Nov19	Nov23	Dec13	Feb16	Nov30	Jan15	Apr12	Aug12	Tot.
First hours									
Gains (M$)	0.6	1.6	2.1	1.4	0.4	4.4	2.7	0.1	13
MSA (%)	80	77	100	50	93	100	94	134	90
Direct (%)	6	43	91	74	11	94	15	166	63
All hours									
Gains (M$)	2.1	1.6	9.5	18.0	3.1	9.8	9.2	13.5	67
MSA (%)	90	78	97	88	93	104	95	104	96
Direct (%)	14	44	55	87	16	145	29	118	83

Notes: This table shows TransAlta's gross gains from manipulations (in million dollars) separately for each event during the first hours, and all hours of the outages. MSA (%) provides the relative size of the regulator's estimate compared to ours. Direct (%) gives the share of gains associated with the outage assuming no strategic reactions from TransAlta and its rivals.

Table 9: Welfare impacts

	Nov19	Nov23	Dec13	Feb16	Nov30	Jan15	Apr12	Aug12	Tot.
First hours									
Transfer (M$)	5.0	13.6	19.0	11.9	3.8	37.8	23.8	0.5	115
MSA (%)	81	83	100	33	92	100	95	125	89
Direct (%)	6	48	93	66	11	96	16	152	64
All hours									
Gains (M$)	18.5	13.5	83.8	165.6	31.8	85.3	78.3	119.4	596
MSA (%)	90	84	98	85	90	104	96	104	95
Direct (%)	15	49	56	81	14	149	31	119	82

Notes: This table shows the transfer from buyers to sellers caused by the manipulations (in million dollars) separately for each event during the first hours, and all hours of the outages. MSA (%) provides the relative size of the regulator's estimate compared to ours. Direct (%) gives the share of transfers associated with the outage assuming no strategic reactions from TransAlta and its rivals.

A Mathematical Appendix

Proposition 1 (Sequential markets under uncertainty) *In equilibrium, the monopolist's forward commitments $Q_1^\star$ and final output $Q_1^\star + Q_2^\star$ decrease with its marginal cost $1/B$ and the slope of its residual demand b. In addition,*

- *(Forward seller) $Q_1^\star \geq 0$ if only if $\alpha \geq \underline{\alpha} = \frac{B+b}{2B+b}$;*
- *(Spot seller) $Q_2^\star \geq 0$ if and only if $p_2^\star \geq C(Q_1^\star + Q_2^\star)$; and,*
- *(Forward premium) $p_1^\star \geq E[p_2^\star]$ if only if $\alpha \geq \underline{\alpha}$;*

Proof 1 (Proof of Proposition 1) *Solving backward, we consider first the profit-maximization problem of the monopolist in period 2, when uncertainty is resolved. Given p_1 and Q_1, the problem writes*

$$\max_{Q_2} \quad \Pi = p_1 Q_1 + \frac{1}{b}\left(A - Q_1 - Q_2\right) Q_2 - \int_0^{Q_1+Q_2} C(Q)dQ. \tag{19}$$

The first-order condition is

$$\begin{aligned} \frac{\partial \Pi}{\partial Q_2} = 0 &= \frac{\partial p_2}{\partial Q_2} Q_2 + p_2 - C(Q_1 + Q_2) \\ &= \frac{1}{b}\left(A - Q_1 - 2Q_2\right) - \frac{1}{B}\left(Q_1 + Q_2\right) \end{aligned} \tag{20}$$

and the quantity supplied in period 2 is thus

$$Q_2^\star = \frac{B}{2B+b} A - \frac{B+b}{2B+b} Q_1. \tag{21}$$

Result 2 follows from the first-order condition in (20) which can be rewritten $Q_2^\star / b = p_2^\star - \left(Q_1^\star + Q_2^\star\right)/B$.

In period 1, the expected profit maximization program is given by

$$\max_{Q_1} \quad E[\Pi] = \frac{1}{b}\left(\alpha E[A] - Q_1\right) Q_1 + E\left[\frac{1}{b}\left(A - Q_1 - Q_2^\star\right) Q_2^\star\right] - E\left[\int_0^{Q_1+Q_2^\star} C(Q)dQ\right]. \tag{22}$$

Making use of the envelope theorem, the first-order condition is

$$\begin{aligned}\frac{\partial E[\Pi]}{\partial Q_1} = 0 &= \frac{\partial p_1}{\partial Q_1} Q_1 + p_1 + E\left[\frac{\partial p_2}{\partial Q_1} Q_2^\star\right] - E\left[C(Q_1 + Q_2^\star)\right] \\ &= \frac{1}{b}\left(\alpha E[A] - 2Q_1 - E[Q_2^\star]\right) - \frac{1}{B}\left(Q_1 + E[Q_2^\star]\right),\end{aligned} \tag{23}$$

or equivalently

$$\frac{\partial E[\Pi]}{\partial Q_1} = \frac{1}{b}\left\{\alpha E(A) - \frac{3B + 2B}{2B + b} Q_1 - \frac{B + b}{2B + b} E(A)\right\} = 0. \tag{24}$$

The quantity supplied in period 1 is such that

$$Q_1^\star = \frac{B}{2B + b}\alpha E[A] - \frac{B + b}{2B + b} E[Q_2^\star]. \tag{25}$$

From (21)*, in equilibrium, the monopolist's forward sales are*

$$Q_1^\star = \frac{(2\alpha - 1)B - (1 - \alpha)b}{3B + 2b} E[A]. \tag{26}$$

which yields the first result, and its total output is

$$Q_1^\star + Q_2^\star = \frac{B}{2B + b}(A - E[A]) + \frac{(1 + \alpha)B}{3B + 2b} E[A]. \tag{27}$$

The forward price is

$$p_1^\star = (1 + \alpha)\frac{B + b}{3B + 2b}\frac{E[A]}{b}, \tag{28}$$

and the spot price is

$$p_2^\star = \frac{A}{b}\frac{B+b}{2B+b} + \frac{E[A]}{b}\left(\frac{B}{2B+b} - \frac{(1+\alpha)B}{3B+2b}\right). \tag{29}$$

The spread between the forward and spot markets depend on the realization of demand and the forward demand $\alpha E[A]$. It is given by

$$p_2^\star - p_1^\star = \frac{A}{b}\frac{B+b}{2B+b} + \frac{E[A]}{b}\left(\frac{B}{2B+b} - \frac{(1+\alpha)(2B+b)}{3B+2b}\right), \tag{30}$$

and the expected price spread between the sequential markets is given by

$$\begin{aligned} p_1^\star - E[p_2^\star] &= \left(\alpha - \frac{B+b}{2B+b}\right)\frac{E(A)}{b} - \frac{B+b}{2B+b}\frac{Q_1^\star}{b} \\ &= \frac{(2\alpha-1)B-(1-\alpha)b}{3B+2b}\frac{E[A]}{b}. \end{aligned} \tag{31}$$

yielding Result 3 in the proposition.

Moreover, feasibility requires $Q_1^\star + Q_2^\star \geq 0$ and $q_1^\star + q_2^\star \geq 0$. From (27), the first condition is satisfied if $F(\cdot)$ is such that

$$Pr(A < -\frac{(2\alpha-1)B-(1-\alpha)b}{3B+2b}E[A]) = 0, \tag{32}$$

and the second condition is equivalent to $A - (Q_1^\star + Q_2^\star) \geq 0$ which holds if $F(\cdot)$ is such that

$$Pr(A < \frac{B}{B+b}\frac{(2\alpha-1)B-(1-\alpha)b}{3B+2b}E[A]) = 0. \tag{33}$$

Proof 2 (Endogenous α in this context) *Risk-neutral consumers choose α to minimize their total expected expenditures to procure A. This problem is given by*

$$\min_{\alpha} \quad E[TE] = \alpha p_1 E[A] + E\left[p_2\left(A - \alpha E[A]\right)\right]. \tag{34}$$

The optimal share denoted $\alpha^\star$ is characterized by the first-order condition

$$\begin{aligned}\frac{\partial E\left[TE\right]}{\partial \alpha} &= 0 = \left(p_1 + \alpha\frac{\partial p_1}{\partial \alpha} - E[p_2]\right) E(A) + E\left[\frac{\partial p_2}{\partial \alpha}(A - \alpha E[A])\right] \\ &= \frac{1}{b}\left(\alpha E[A] - Q_1 + \alpha E(A) - \alpha\frac{\partial Q_1}{\partial \alpha} - E[A] + Q_1 + E[Q_2]\right) E(A) + E\left[\frac{\partial p_2}{\partial \alpha}(A - \alpha E[A])\right] \\ &= \frac{1}{b}\left((2\alpha - 1)E[A] - \alpha\frac{\partial Q_1}{\partial \alpha} + E[Q_2]\right) E(A) - \frac{1}{b}E\left[\frac{\partial (Q_1 + Q_2)}{\partial \alpha}(A - \alpha E[A])\right]\end{aligned} \tag{35}$$

where

$$\begin{aligned}\frac{\partial Q_1}{\partial \alpha} &= \frac{2B + b}{3B + 2b}E(A), \\ E(Q_2) &= \frac{(2 - \alpha)B + (1 - \alpha)b}{3B + 2b}E(A), \\ \frac{\partial Q_1 + Q_2}{\partial \alpha} &= \frac{B}{3B + 2b}E(A).\end{aligned} \tag{36}$$

Substituting and rearranging yield

$$\begin{aligned}0 &= \frac{1}{b}\left((2\alpha - 1)(3B + 2b) - \alpha(2B + b) + B + (1 - \alpha)b\right)\frac{E(A)^2}{3B + 2b}, \\ 0 &= \frac{1}{b}(2\alpha - 1)(2B + b)\frac{E(A)^2}{3B + 2b},\end{aligned} \tag{37}$$

which implies that it is optimal for consumers to choose $\alpha^\star = 1/2$. This solution is feasible only if the monopolist produces a positive output, i.e. if $Q_1^\star + Q_2^\star \geq 0$ which is guaranteed under the previous feasibility conditions on $F(A)$.

Proposition 2 (All-or-nothing strategic reneging) *In equilibrium, taking forward commitments as given, there exists a demand threshold T such that $R = \mu Q_1$ if and only if $A \geq T$, and $R = 0$ otherwise. In addition, T increases with τ and p_1, and decreases with μ and Q_1.*

Proof 3 (Proof of Proposition 2) *We first show that the problem admits a corner solution, then characterize the demand threshold T.*

Part 1 (Corner solution). *The first-order condition with respect to* Q_2 *is changed to*

$$\begin{aligned}\frac{\partial \Pi}{\partial Q_2} = 0 &= \frac{\partial p_2}{\partial Q_2} Q_2 + p_2 - C(Q_1 - R + Q_2) \\ &= \frac{1}{b}\left(A - Q_1 + R - 2Q_2\right) - \frac{1}{B}\left(Q_1 - R + Q_2\right),\end{aligned} \tag{38}$$

and thus we have

$$Q_2^{\dagger} = \frac{B}{2B+b} A - \frac{B+b}{2B+b}(Q_1 - R). \tag{39}$$

The first-order condition with respect to R *is*

$$\begin{aligned}\frac{\partial \Pi}{\partial R} = 0 &= -(p_1 + \tau) + \frac{\partial p_2}{\partial R} Q_2 + C(Q_1 - R + Q_2) \\ &= -(p_1 + \tau) + \frac{1}{b} Q_2 + \frac{1}{B}\left(Q_1 - R + Q_2\right),\end{aligned} \tag{40}$$

However, this condition does not characterize the optimal reneging strategy. The set of first-order conditions does not characterize a maximum because we have $\left(\partial^2 \Pi / \partial Q_2^2\right)^2 = -\left(2/b + 1/B\right) < 0$ *and the determinant*

$$\frac{\partial^2 \Pi}{\partial Q_2^2} \frac{\partial^2 \Pi}{\partial R^2} - \left(\frac{\partial^2 \Pi}{\partial Q_2 \partial R}\right) = -\frac{1}{b^2} < 0. \tag{41}$$

To solve this problem, let us consider R *to be fixed at the time of choosing* Q_2*, so that* (39) *holds. Substituting its expression into* (40) *yields*

$$\frac{\partial \Pi}{\partial R} = -(p_1 + \tau) + \left(\frac{1}{b} + \frac{1}{B}\right)\left(\frac{B}{2B+b} A - \frac{B+b}{2B+b}(Q_1 - R)\right) + \frac{1}{B}\left(Q_1 - R\right). \tag{42}$$

Differentiating with respect to R gives

$$\begin{aligned}\frac{\partial^2 \Pi}{\partial R^2} &= \left(\frac{1}{b} + \frac{1}{B}\right)\left(\frac{B+b}{2B+b}\right) - \frac{1}{B} \\ &= \frac{B}{b(2B+b)} > 0,\end{aligned} \tag{43}$$

that is the objective function is convex in R, leading to a corner solution. The optimal reneging strategy is an all-or-nothing strategy, i.e. $R^\star = 0$ or $R^\star = \mu Q_1$.

Part 2 (Demand threshold). *Reneging is profitable for all A such that*

$$\Pi^\dagger(A) - \Pi^\star(A) \geq 0, \tag{44}$$

which develops into

$$\Pi^\dagger(A) - \Pi^\star(A) = \frac{2(B+b)A - B(2-\mu)Q_1}{2b(2B+b)}\mu Q_1 - (p_1+\tau)\mu Q_1 \geq 0. \tag{45}$$

If $Q_1 > 0$, then reneging is optimal for all $A \geq T$, where

$$T = (p_1+\tau)\frac{b(2B+b)}{B+b} + \frac{B}{2(B+b)}(2-\mu)Q_1. \tag{46}$$

It is easily checked that this threshold satisfies

$$\begin{aligned}
\frac{\partial T}{\partial \tau} &= \frac{b(2B+b)^2}{2B^2+b(3B+b)} > 0, \\
\frac{\partial T}{\partial \mu} &= -\frac{B(2B+b)}{2(2B^2+b(3B+b))} Q_1 < 0, \ \textit{and}, \\
\frac{\partial T}{\partial Q_1} &= \frac{\partial p_1}{\partial Q_1} \frac{b(2B+b)}{B+b} + \frac{B}{2(B+b)}(2-\mu) \\
&= \frac{-2(2B+b)+B(2-\mu)}{2(B+b)} \\
&= -\frac{(2+\mu)B+2b}{2(B+b)} < 0.
\end{aligned} \tag{47}$$

The development in (45) *is obtained from the addition of*

$$\begin{aligned}
\Delta p_2 Q_2^\star &= \frac{1}{b(2B+b)^2}\left(B^2 A - B(B+b)(1-\mu)Q_1\right)\mu Q_1, \ \textit{and}, \\
p_2^\star \Delta Q_2^\star &= \frac{1}{b(2B+b)^2}\left((B+b)^2 A - B(B+b)Q_1\right)\mu Q_1,
\end{aligned}$$

which yields

$$\Delta p_2 Q_2^\star + p_2^\star \Delta Q_2^\star = \frac{1}{b(2B+b)^2}\left((B^2+(B+b)^2)A - B(B+b)(2-\mu)Q_1\right)\mu Q_1,$$

and from which we finally obtain

$$\begin{aligned}
\Delta p_2 Q_2^\star + p_2^\star \Delta Q_2^\star + \Delta C &= \frac{(2(B^2+(B+b)^2+2Bb)A - (2B(B+b)-Bb)(2-\mu)Q_1)}{2b(2B+b)^2}\mu Q_1 \\
&= \frac{((4B^2+2b(3B+b))A - B(2B+b)(2-\mu)Q_1)}{2b(2B+b)^2}\mu Q_1.
\end{aligned}$$

Proposition 3 (Spot strategy) *In equilibrium, if reneging is profitable ($A \geq T$), the monopolist will shift its spot supply to $Q_2^\dagger > Q_2^\star$ to optimize its profits, total production decreases and, in addition,*

- *(Price impact) $\Delta p_2 \geq 0$ increases with μ, Q_1, $1/b$, and B;*

- *(Strategy shift)* $\Delta Q_2 \geq 0$ *increases with* μ, Q_1, b *and* $1/B$; *and,*

- *(Cost savings)* $\Delta C \geq 0$ *increases with* μ, Q_1 *and* $1/b$, *and the effect of* $1/B$ *depends on the relative cost advantage of the monopolist.*

Proof 4 (Proof of Proposition 3) *The first two results are directly obtained from*

$$\begin{aligned}
\Delta p_2 &= \frac{B}{b(2B+b)}\mu Q_1 \\
\Delta Q_2 &= \frac{B+b}{2B+b}\mu Q_1,
\end{aligned}$$

and the third result follows from the expression

$$\begin{aligned}
\Delta C = \int_{(1-\mu)Q_1+Q_2^\dagger}^{Q_1+Q_2^\star} C(Q)dQ &= \int_{\frac{B}{2B+b}(A+(1-\mu)Q_1)}^{\frac{B}{2B+b}(A+Q_1)} C(Q)dQ \\
&= \frac{1}{2B}\frac{B^2}{(2B+b)^2}\left((A+Q_1)^2 - (A+(1-\mu)Q_1)^2\right) \\
&= \frac{B}{2(2B+b)^2}\left(2\mu A Q_1 + \mu(2-\mu)Q_1^2\right) \\
&= \frac{B}{2(2B+b)^2}\left(2A + (2-\mu)Q_1\right)\mu Q_1.
\end{aligned}$$

This expression is derived by combining and rearranging the following expressions:

$$\begin{aligned}
Q_1 + Q_2^\star &= \frac{B}{2B+b}(A+Q_1), \\
(1-\mu)Q_1 + Q_2^\dagger &= \frac{B}{2B+b}(A+(1-\mu)Q_1), \\
Q_2^\star &= \frac{B}{2B+b}A - \frac{B+b}{2B+b}Q_1, \ \textit{and,} \\
Q_2^\dagger &= \frac{B}{2B+b}A - \frac{B+b}{2B+b}(1-\mu)Q_1.
\end{aligned}$$

Proposition 4 (Equilibrium forward sales) *In equilibrium, upon anticipating a positive probability of profitable reneging, the monopolist will shift its supply of forward contracts to* $Q_1^\dagger > Q_1^\star$, *the extent of which depends on the distribution of uncertainty.*

The monopolist faces a trade-off upon choosing Q_1. In equilibrium, the firm will equalize the expected marginal efficiency loss associated with excessive forward sales with the expected marginal profit associated with spot market manipulation. Upon increasing its forward sales, the monopolist increases both the likelihood of a profitable manipulation $1-F(T)$ and the profitability of the latter. This comes at the opportunity cost of "over contracting" when $A \leq T$.

Proof 5 (Proof of Proposition 4) *The first-order condition is*

$$\frac{\partial E[\Pi]}{\partial Q_1} = 0, \tag{48}$$

where

$$\begin{aligned}\frac{\partial E[\Pi]}{\partial Q_1} = & \frac{\partial T}{\partial Q_1} f(T)\left(\Pi^\star(T) - \Pi^\dagger(T)\right) + \int_0^T \frac{\partial \Pi^\star(A)}{\partial Q_1} dF(A) \\ & + \int_T^{+\infty} \frac{\partial \Pi^\dagger(A)}{\partial Q_1} dF(A).\end{aligned} \tag{49}$$

The definition of T implies $\Pi^\star(T) = \Pi^\dagger(T)$ and the condition becomes

$$\int_0^T \frac{\partial \Pi^\star(A)}{\partial Q_1} dF(A) + \int_T^{+\infty} \frac{\partial \Pi^\dagger(A)}{\partial Q_1} dF(A) = 0, \tag{50}$$

The second-order condition is given by

$$\begin{aligned}\frac{\partial^2 E[\Pi]}{\partial Q_1^2} = & \frac{\partial T}{\partial Q_1} f(T)\left(\frac{\partial \Pi^\star(T)}{\partial Q_1} - \frac{\partial \Pi^\dagger(T)}{\partial Q_1}\right) \\ & + \int_0^T \frac{\partial^2 \Pi^\star(A)}{\partial Q_1^2} dF(A) + \int_T^{+\infty} \frac{\partial^2 \Pi^\dagger(A)}{\partial Q_1^2} dF(A).\end{aligned} \tag{51}$$

The first term is negative since $\frac{\partial T}{\partial Q_1} < 0$, $f(T) > 0$ *and* $\left(\frac{\partial \Pi^\star(T)}{\partial Q_1} - \frac{\partial \Pi^\dagger(T)}{\partial Q_1}\right) > 0$ *since*

$$\begin{aligned}
\frac{\partial \Pi^\dagger(T) - \Pi^\star(T)}{\partial Q_1} =& \mu \left[\frac{(2(B+b)T - B(2-\mu)Q_1)}{2b(2B+b)} - (p_1 + \tau) \right] \\
=& -\mu Q_1 \left(\frac{B(2-\mu)}{2b(2B+b)} + \frac{\partial p_1}{\partial Q_1} \right) \\
=& -\mu Q_1 \left(\frac{B(2-\mu) - 2(2B+b)}{2b(2B+b)} \right) \\
=& \mu Q_1 \left(\frac{(2+\mu)B + 2b}{2b(2B+b)} \right) > 0.
\end{aligned} \tag{52}$$

The two last terms of (51) *are negative so the first-order condition characterizes a maximum.*

The integrand of the first term in (50) *can be developed into*

$$\begin{aligned}
\frac{\partial \Pi^\star(A)}{\partial Q_1} &= \frac{\partial p_1}{\partial Q_1} Q_1 + p_1 + \frac{\partial p_2^\star}{\partial Q_1} Q_2^\star - C(Q_1 + Q_2^\star) \\
&= \frac{1}{b} \left(\alpha E(A) - 2Q_1 - Q_2^\star \right) - \frac{Q_1 + Q_2^\star}{B}, \\
&= \frac{\alpha E(A)}{b} - \frac{2B+b}{Bb} Q_1 - \frac{B+b}{Bb} Q_2^\star, \\
&= \frac{\alpha E(A)}{b} - \frac{2B+b}{Bb} Q_1 - \frac{B+b}{Bb} \left(\frac{B}{2B+b} A - \frac{B+b}{2B+b} Q_1 \right), \\
&= \frac{\alpha E(A)}{b} - \frac{3B+2B}{b(2B+b)} Q_1 - \frac{B+b}{b(2B+b)} A.
\end{aligned} \tag{53}$$

Thus, we have

$$\int_0^T \frac{\partial \Pi^\star(A)}{\partial Q_1} dF(A) = \left(\frac{\alpha E(A)}{b} - \frac{3B+2B}{b(2B+b)} Q_1 - \frac{B+b}{b(2B+b)} E[A|A \leq T] \right) F(T). \tag{54}$$

The integrand of the second term in (50) *can be developed into*

$$
\begin{aligned}
\frac{\partial \Pi^{\dagger}(A)}{\partial Q_1} &= (1-\mu)\left[\frac{\partial p_1}{\partial Q_1}Q_1 + p_1 - C((1-\mu)Q_1 + Q_2^{\dagger})\right] - \mu\tau + \frac{\partial p_2^{\dagger}}{\partial Q_1}Q_2^{\dagger} \\
&= (1-\mu)\left[\frac{\partial p_1}{\partial Q_1}Q_1 + p_1 - \frac{1}{b}Q_2^{\dagger} - C((1-\mu)Q_1 + Q_2^{\dagger})\right] - \mu\tau \\
&= (1-\mu)\left[\frac{\alpha E(A)}{b} - \frac{2B + b(1-\mu)}{Bb}Q_1 - \frac{B+b}{Bb}Q_2^{\dagger}\right] - \mu\tau \\
&= (1-\mu)\left[\frac{\alpha E(A)}{b} - \frac{2B + b(1-\mu)}{Bb}Q_1 - \frac{B+b}{Bb}\left(\frac{B}{2B+b}A - \frac{B+b}{2B+b}(1-\mu)Q_1\right)\right] - \mu\tau \\
&= (1-\mu)\left[\frac{\alpha E(A)}{b} - \left(\frac{2B + b(1-\mu)}{Bb} - \frac{(B+b)^2(1-\mu)}{Bb(2B+b)}\right)Q_1 - \frac{B+b}{b(2B+b)}A\right] - \mu\tau \\
&= \frac{(1-\mu)}{b}\left[\alpha E(A) - \frac{(3+\mu)B + 2b}{(2B+b)}Q_1 - \frac{B+b}{(2B+b)}A\right] - \mu\tau
\end{aligned}
\tag{55}
$$

Thus, we have

$$
\begin{aligned}
\int_T^{+\infty} \frac{\partial \Pi^{\dagger}(A)}{\partial Q_1} dF(A) =& (1-\mu)\left(\frac{\alpha E(A)}{b} - \frac{(3+\mu)B + 2b}{b(2B+b)}Q_1 - \frac{B+b}{b(2B+b)}E[A|A>T]\right)(1-F(T)) \\
& - \mu\tau\,(1-F(T))\,.
\end{aligned}
\tag{56}
$$

Combining and rearranging yields the equivalent expression of the first-order condition

$$
\begin{aligned}
&\frac{(1-\mu\,(1-F(T)))}{b}\left\{\alpha E(A) - \frac{3B+2B}{2B+b}Q_1 - \frac{B+b}{2B+b}E(A)\right\} + \\
&\frac{\mu\,(1-F(T))}{b}\left\{\frac{B+b}{2B+b}\,(E[A|A>T] - E(A)) - \frac{(1-\mu)\,B}{2B+b}Q_1 - b\tau\right\} = 0.
\end{aligned}
\tag{57}
$$

From (24)*, the first term in* (57) *is equal to zero for* $Q_1^{\star}$*. Furthermore, we have* $T \leq E[A|A>T]$ *hence the second term between braces admits as minimum bound*

$$
\frac{B+b}{2B+b}\,(T - E(A)) - \frac{(1-\mu)\,B}{2B+b}Q_1 - b\tau. \tag{58}
$$

Substituting p_1 by its expression into (46) *yields*

$$T = \alpha E(A)\frac{2B+b}{B+b} - Q_1\frac{(2+\mu)B+2b}{2(B+b)} + \tau b\frac{2B+b}{B+b}, \tag{59}$$

which substituting into (58) *and rearranging yields another expression for this bound*

$$E(A)\frac{B(2\alpha-1)-b(1-\alpha)}{2B+b} - Q_1\frac{\frac{4-\mu}{2}B+b}{2B+b}. \tag{60}$$

It is easily checked that this bound is positive at $Q_1^\star$. Therefore for any parameter values (provided that $Q_1^\star$ is positive) the solution of (57) *will be above $Q_1^\star$.*

Is there a forward premium? The forward premium is decreased by strategic reneging even without anticipatory adjustments in the forward market (*i.e.* with $Q_1^\dagger = Q_1^\star$) because the spot price will be larger in expectations. More importantly, there is a range of forward covers $[\underline{\alpha}, \overline{\alpha}]$ for which a spot price premium is sustained in equilibrium (Proposition 5). It follows in particular that for $\alpha = \overline{\alpha}$ there is price convergence and the monopolist is a seller in both markets. This convergence exists in our setting *because* the monopolist exerts market power and manipulates the spot price via strategic reneging, and not because of arbitrage and increased competition. This result shows the limit of using price convergence as a metric to measure competitiveness in sequential imperfect markets.[60]

Remark that buyers now face a trade-off. Indeed, taking more forward contracts to hedge against higher spot prices (and volatility) will provide more room for manipulation to the monopolist. Although useful to deal with uncertainties, forward markets may introduce distortions into market mechanisms.

[60]This point was already made by Ito and Reguant (2016) in a setup with market power and limited arbitrage. In their setting, more arbitrage leads to more competitive outcomes on average but enlarges the deadweight loss during periods where the strategic player enjoys high market power.

Proposition 5 (Equilibrium forward premium) *In equilibrium, there is a forward premium $p_1^\dagger \geq E[p_2^\dagger]$ if and only if $\alpha \geq \overline{\alpha} > \underline{\alpha}$, and $p_1^\dagger < E[p_2^\dagger]$ otherwise. In addition, $\overline{\alpha} < 1$ in absence of a forward adjustment, i.e. if $Q_1^\dagger = Q_1^\star$.*

Proof 6 (Proof of Proposition 5) *The results are easily checked from* (31) *and its analog under imperfect commitment is given by*

$$\begin{aligned} p_1^\dagger - E[p_2^\dagger] = &\left(\alpha - \frac{B+b}{2B+b}\right)\frac{E(A)}{b} \\ &- \left(\frac{B+b}{2B+b} + \mu(1-F(T))\frac{B}{2B+b}\right)\frac{Q_1^\dagger}{b}. \end{aligned} \tag{61}$$

Assuming further that $Q_1^\dagger = Q_1^\star$, the condition for a forward premium to be sustained, i.e. $p_1^\dagger \geq E[p_2^\dagger]$, simplifies to

$$\left(\alpha - \frac{B+b}{2B+b} - \frac{(1+\mu(1-F(T)))B+b}{2B+b}\frac{B}{3B+2b}\right)\frac{E(A)}{b} \geq 0. \tag{62}$$

Under this assumption, the threshold level of contracting $\overline{\alpha}$ is hence such that

$$\underline{\alpha} < \overline{\alpha} = \underline{\alpha} + \frac{(1+\mu(1-F(T)))B+b}{2B+b}\frac{B}{3B+2b} \leq \underline{\alpha} + \frac{B}{3B+2b} < 1. \tag{63}$$

Proposition 6 (Piecewise linear residual demand) *In equilibrium, if the residual demand is a piecewise linear function with a discontinuity at $Q_2^k < Q_2^\star$, there exists a demand threshold $\tilde{A}$ above which it is profitable to trigger the price step Δc by producing Q_2^k instead of $Q_2^\star$. In addition,*

- *(Spot) The threshold $\tilde{A}$ decreases with Δc, and increases with k and Q_1;*
- *(Forward) The firm will also reduce its forward commitments to $Q_1^k < Q_1^\star$; and,*
- *(Reneging) The price step makes strategic reneging profitable for lower values of demand, i.e. there exists $\tilde{T} < T$ above which strategic reneging is profitable for*

any demand A for large enough values of Δc.

Proof 7 (Proof of Proposition 6) *Following the specification of the fringe's marginal cost function, let us define $Q_2^k = A - Q_1 - k$ as the dominant player's maximum volume of spot sales such that the fringe marginal cost is $q/b + \Delta c$ (i.e. on the upper segment). The equilibrium condition in the spot market is changed to:*

$$Q_2 = A - Q_1 + b\Delta c - bp_2 \text{ for any } 0 \leq Q_2 \leq Q_2^k,$$
$$Q_2 = A - Q_1 - bp_2 \text{ for any } Q_2 > Q_2^k.$$

Over the interval where $Q_2 \in \left[0, Q_2^k\right]$ the price is given by

$$p_2 = \frac{1}{b}\left(A - Q_1 + b\Delta c - Q_2\right)$$

hence the profit function is given by

$$\begin{aligned}\Pi &= p_1 Q_1 + p_2 Q_2 - \int_0^{Q_1+Q_2} C(Q)dQ \\ &= p_1 Q_1 + \frac{1}{b}\left(A - Q_1 + b\Delta c - Q_2\right) Q_2 - \frac{1}{B}\int_0^{Q_1+Q_2} QdQ.\end{aligned}$$

Part 1. Optimal strategy without reneging. *The optimal strategy is given by*

$$\frac{\partial \Pi}{\partial Q_2} = \frac{1}{b}\left(A - Q_1 + b\Delta c - 2Q_2\right) - \frac{1}{B}\left(Q_1 + Q_2\right)$$

so that

$$\overline{Q}_2 = \frac{B}{2B+b}\left(A + b\Delta c\right) - \frac{B+b}{2B+b} Q_1$$

if $Q_2 \leq Q_2^k$, and $Q_2^\star$ defined in (21) if $Q_2 > Q_2^k$.

For given values of A and Q_1, we have $\overline{Q}_2 > Q_2^\star$ because $\Delta c > 0$ although the *feasibility conditions dictate that the strategy* $\overline{Q}_2$ *prevails over* $Q_2 \in \left[0, Q_2^k\right]$ *and* $Q_2^\star$ *prevails for "large" values of* Q_2 *(*$Q_2 > Q_2^k$*). Observe that:*

- *If* $Q_2^\star(A, Q_1) < Q_2^k(A, Q_1)$ *then the optimal strategy over* $\left[Q_2^k; +\infty\right[$ *is* Q_2^k *(the profit function is decreasing on* $[Q_2^\star; +\infty[\cap \left[Q_2^k; +\infty\right[$ *).*
- *If* $\overline{Q}_2(A, Q_1) > Q_2^k(A, Q_1)$ *then the optimal strategy over* $\left[0; Q_2^k\right]$ *is* Q_2^k *(the profit function is increasing on* $\left[0; \overline{Q}_2\right] \cap \left[0; Q_2^k\right]$ *).*

There are three cases:

1. *If* $Q_2^\star < Q_2^k < \overline{Q}_2$ *then the optimal strategy is* Q_2^k*.*
2. *If* $Q_2^\star < \overline{Q}_2 < Q_2^k$ *then the optimal strategy is* $\overline{Q}_2$*.*
3. *If* $Q_2^k < Q_2^\star < \overline{Q}_2$ *then we must compare profits for* Q_2^k *and* $Q_2^\star$*.*

We compare the profits in each case to characterize this case. Let $\Pi^\star$*,* $Q_2^\star$ *and* Q_2^k *be given as above and define*

$$\delta = Q_2^\star - Q_2^k,$$

that can be positive or negative. By definition

$$\begin{aligned} p_2(Q_2^k) &= \frac{1}{b}\left(A - Q_1 - Q_2^k\right) \\ &= \frac{1}{b}\left(A - Q_1 - Q_2^\star - \left(Q_2^k - Q_2^\star\right)\right) \\ &= p_2^\star + \frac{\delta}{b} \end{aligned}$$

if $Q_2 > Q_2^k$*. The lower price at the step (at* $Q_2^k + \varepsilon$*) is thus* $p_2^\star + \delta/b$*. The upper price* *is* $p_2^\star + (\delta/b) + \Delta c$. *The profit obtained with strategy* Q_2^k *writes*

$$\begin{aligned}
\Pi^k &= p_1 Q_1 + p_2 Q_2^k - \int_0^{Q_1+Q_2^k} C(Q)dQ \\
&= p_1 Q_1 + \left(p_2^\star + \frac{\delta}{b} + \Delta c\right)(Q_2^\star - \delta) - \frac{1}{B}\int_0^{Q_1+Q_2^\star+\delta} QdQ \\
&= p_1 Q_1 + \left(p_2^\star + \frac{\delta}{b} + \Delta c\right)(Q_2^\star - \delta) - \frac{1}{2B}\left(Q_1 + Q_2^\star - \delta\right)^2 \\
&= p_1 Q_1 + p_2^\star Q_2^\star + \left[\Delta c Q_2^\star + \left(p_2^\star + \Delta c - \frac{Q_2^\star}{b}\right)\delta - \frac{\delta^2}{b}\right] \\
&- \frac{1}{2B}\left[\left(Q_1 + Q_2^\star\right)^2 - 2\delta\left(Q_1 + Q_2^\star\right) + \delta^2\right] \\
&= \Pi^\star + \left[\Delta c Q_2^\star - \left(p_2^\star + \Delta c - \frac{Q_2^\star}{b}\right)\delta - \frac{\delta^2}{b}\right] - \frac{1}{2B}\left[-2\delta\left(Q_1 + Q_2^\star\right) + \delta^2\right].
\end{aligned}$$

It is therefore profitable to choose Q_2^k *rather than* $Q_2^\star$ *if*

$$\Delta c Q_2^\star > \delta\left\{-\frac{1}{2B}\left[2\left(Q_1 + Q_2^\star\right) - \delta\right] + \left[p_2^\star - \frac{1}{b}Q_2^\star + \frac{\delta}{b} + \Delta c\right]\right\}.$$

Since $Q_2^\star$ *is optimal we know that it satisfies:*

$$p_2^\star - \frac{1}{b}Q_2^\star = \frac{1}{B}\left(Q_1 + Q_2^\star\right)$$

from the FOC in (20) *therefore the previous inequality boils down to:*

$$\Delta c Q_2^\star > \delta\left[\Delta c + \left(\frac{1}{2B} + \frac{1}{b}\right)\delta\right]$$

which yields the condition

$$\Delta c Q_2^k > \left(\frac{1}{2B} + \frac{1}{b}\right)\delta^2. \tag{64}$$

Observe that a negative shift from $Q_2^\star$ *to* Q_2^k *to trigger* Δc *is more likely when* Q_2^k *is large,* Δc *is large,* δ *is small,* b *is large (RD is less elastic).*

Let us denote $W = \Delta c Q_2^k - \left(\frac{1}{2B} + \frac{1}{b}\right)\delta^2$ *and differentiate to obtain*

$$\frac{\partial W}{\partial A} = \Delta c + \frac{B+b}{Bb}\delta > 0 \qquad (65)$$

since $\delta > 0$ *when* $Q_2^k < Q_2^\star$. *Moreover,*

$$\frac{\partial^2 W}{\partial A^2} < 0, \qquad (66)$$

thus there is a threshold level of demand $\tilde{A}$ *such that for all* $A > \tilde{A}$ *(assuming* $\delta > 0$ *though),* Q_2^k *yields larger profits than* $Q_2^\star$ *and reversely for lower values of* A. *This threshold is characterized by*

$$\begin{aligned} W &= \Delta c Q_2^k - \left(\frac{1}{2B} + \frac{1}{b}\right)\delta^2 = 0 \\ \leftrightarrow \Delta c(\tilde{A} - Q_1 - k) &= \left(\frac{1}{2B} + \frac{1}{b}\right)\left(k - \frac{B+b}{2B+b}\tilde{A} + \frac{B}{2B+b}Q_1\right)^2. \end{aligned} \qquad (67)$$

Total differentiation and rearrangement yield the relation between this threshold and forward commitments

$$0 < \frac{d\tilde{A}}{dQ_1} = \frac{\Delta c + \frac{1}{b}\delta}{\Delta c + \frac{B+b}{Bb}\delta} < 1. \qquad (68)$$

Part 2. Strategy on forward markets. *A complete characterization of the optimal forward strategy requires solving several cases depending on the distribution of demand. To gain intuition of the effect of discontinuities on the forward strategy, we only focus on a specific case where demand is distributed so that* $Q_2^k < Q_2^\star$, *i.e.* $A < \frac{2B+b}{B+b}k + \frac{B}{B+b}Q_1$.

In this case, the expected profit is given by

$$
\begin{aligned}
E[\Pi] = &\int_0^{\tilde{A}} \left(p_1 Q_1 + p_2^\star Q_2^\star - \int_0^{Q_1+Q_2^\star} C(Q)dQ \right) dF(A) \\
&+ \int_{\tilde{A}}^{+\infty} \left(p_1 Q_1 + p_2^k Q_2^k - \int_0^{Q_1+Q_2^k} C(Q)dQ \right) dF(A).
\end{aligned} \tag{69}
$$

Differentiating with respect to Q_1, making use of the definition of $\tilde{A}$ and applying the envelope theorem yield

$$
\begin{aligned}
\frac{\partial E[\Pi]}{\partial Q_1} &= \int_0^{\tilde{A}} \left(p_1 - \left(\frac{1}{b} + \frac{1}{B}\right)(Q_1 + Q_2^\star) \right) dF(A) + \int_{\tilde{A}}^{+\infty} \left(p_1 - \left(\frac{1}{b} + \frac{1}{B}\right)\left(Q_1 + Q_2^k\right) \right) dF(A) \\
&\quad - \int_{\tilde{A}}^{+\infty} \left(\frac{\partial p_2^k}{\partial Q_2} Q_2^k + p_2^k - \frac{Q_1 + Q_2^k}{B} \right) dF(A) = 0 \\
&= \int_0^{+\infty} \left(p_1 - \left(\frac{1}{b} + \frac{1}{B}\right)(Q_1 + Q_2^\star) \right) dF(A) \\
&\quad + \int_{\tilde{A}}^{+\infty} \left(\frac{1}{b} + \frac{1}{B}\right)\delta - \left(p_2^k - \frac{Q_1 + Q_2^k}{B} \right) dF(A).
\end{aligned} \tag{70}
$$

The integrand of the second term can be rewritten

$$
\begin{aligned}
&\frac{\delta}{b} + \frac{Q_2^\star - Q_2^k}{B} - p_2^k + \frac{Q_1 + Q_2^k}{B} \\
&= -\frac{Q_2^k}{b} - (p_2^k - p_2^\star) - p_2^\star + \frac{Q_2^\star}{b} + \frac{Q_1 + Q_2^\star}{B} \\
&= -\frac{Q_2^k}{b} - (p_2^k - p_2^\star) < 0,
\end{aligned} \tag{71}
$$

where the inequality holds for the considered case. Therefore the second integral is negative and it must be that the first integral is positive for the first-order condition (70) *to hold. Following the previous result for $Q_1^\star$, it implies that the equilibrium forward commitment is $Q_1^k < Q_1^\star$ in this case.*

Part 3. Reneging under non-linear residual demand. *The complete characterization of strategic reneging in this setting involves solving multiple cases. The most interesting* *case is when reneging would not be profitable without taking advantage of the price jump created by the step function. That is when exerting market power in the spot market and reneging on forward contracts are complementary means to achieve a price impact. We focus on this case by assuming that, for $A = T$,*

- $Q_2^\dagger - Q_2^{\dagger k} = \epsilon > 0$*: reaching the step requires to produce less than the optimal amount* $Q_2^\dagger$ *in presence of reneging; and*
- $\Delta c Q_2^k < \left(\frac{1}{2B} + \frac{1}{b}\right)\left(Q_2^\star - Q_2^k\right)^2$*: the strategy* $Q_2^\star$ *yields larger profits than* Q_2^k *hence the firm will not take advantage of the price step in absence of reneging.*

The first assumption implies $Q_2^k < Q_2^\star$ *because*

$$\begin{aligned} Q_2^\dagger - Q_2^{\dagger k} &= k - \frac{B+b}{2B+b}A + \frac{B}{2B+b}(Q_1 - R) \\ &= \left(Q_2^\star - Q_2^k\right) - \frac{B}{2B+b}R. \end{aligned} \tag{72}$$

In words, without reneging reaching the step also requires producing less than the optimal amount $Q_2^\star$*. This assumption is used to focus on the values of demand for which the step is at the left of the optimal output level in both cases. For some* A*, the increase in profits from combining both reneging and taking advantage of the price step can be written as*

$$\Pi^{\dagger k}(A) - \Pi^\star(A) = \Pi^\dagger(A) - \Pi^\star(A) + p_2^{\dagger k} Q_2^{\dagger k} - p_2^\dagger Q_2^\dagger + \int_{Q_1 - R + Q_2^{\dagger k}}^{Q_1 - R + Q_2^\dagger} C(Q)dQ. \tag{73}$$

Recall that at $A = T$ *the firm is indifferent between choosing* $R = 0$ *and* $R = \mu Q_1$*. At* $A = T$*, the above hence simplifies to*

$$\Pi^{\dagger k}(T) - \Pi^\star(T) = p_2^{\dagger k} Q_2^{\dagger k} - p_2^\dagger Q_2^\dagger + \int_{Q_1 - R + Q_2^{\dagger k}}^{Q_1 - R + Q_2^\dagger} C(Q)dQ, \tag{74}$$

where the second term on the right-hand-side is positive under the previous assumptions.

It can be developed into

$$\int_{Q_1-R+Q_2^{\dagger k}}^{Q_1-R+Q_2^{\dagger}} C(Q)dQ = \frac{1}{B}\left(Q_1 - R + \frac{Q_2^{\dagger} + Q_2^{\dagger k}}{2}\right)\epsilon. \tag{75}$$

Let us now turn to the first term. We have

$$p_2^{\dagger k}Q_2^{\dagger k} - p_2^{\dagger}Q_2^{\dagger} = (p_2^{\dagger k} - p_2^{\dagger})Q_2^{\dagger k} - p_2^{\dagger}(Q_2^{\dagger} - Q_2^{\dagger k}), \tag{76}$$

where at $A = T$,

$$\begin{aligned} p_2^{\dagger k} - p_2^{\dagger} &= \frac{1}{b}(T - (Q_1 - R) - Q_2^{\dagger k}) + \Delta c - p_2^{\dagger} \\ &= \frac{k}{b} + \Delta c - p_2^{\dagger} \\ &= \frac{k}{b} + \Delta c - (p_1 + \tau) - \frac{B}{2B+b}\frac{R}{2b} \\ &= \frac{\epsilon}{b} + \Delta c, \end{aligned} \tag{77}$$

and

$$Q_2^{\dagger} - Q_2^{\dagger k} = k - bp_2^{\dagger} = \epsilon. \tag{78}$$

Making use of these expressions yields

$$p_2^{\dagger k}Q_2^{\dagger k} - p_2^{\dagger}Q_2^{\dagger} = \left(\frac{\epsilon}{b} + \Delta c\right)Q_2^{\dagger k} - p_2^{\dagger}\epsilon. \tag{79}$$

Thus, we have $\Pi^{\dagger k}(T) - \Pi^{\star}(T) > 0$ if and only if

$$\left(\frac{\epsilon}{b} + \Delta c\right)Q_2^{\dagger k} - p_2^{\dagger}\epsilon + \frac{1}{B}\left(Q_1 - R + \frac{Q_2^{\dagger} + Q_2^{\dagger k}}{2}\right)\epsilon > 0, \tag{80}$$

which can be rearranged into

$$
\begin{aligned}
\Delta c Q_2^{\dagger k} &> \left(p_2^{\dagger} - \left(\frac{Q_2^{\dagger k}}{b} + \frac{Q_1 - R}{B} + \frac{Q_2^{\dagger}}{2B} + \frac{Q_2^{\dagger k}}{2B}\right)\right)\epsilon \\
&= \left(p_2^{\dagger} - \frac{Q_2^{\dagger}}{b} - \frac{Q_1 - R + Q_2^{\dagger}}{B}\right)\epsilon + (Q_2^{\dagger} - Q_2^{\dagger k})\left(\frac{1}{b} + \frac{1}{2B}\right)\epsilon \\
&= \left(\frac{1}{b} + \frac{1}{2B}\right)\epsilon^2,
\end{aligned} \tag{81}
$$

where the last equality comes from the definition of ϵ *and the first-order condition for* $Q_2^{\dagger}$. *Therefore, for any* $\epsilon > 0$, *there exists* Δc *such that this condition is satisfied. This condition is not mutually exclusive with* $\Delta c Q_2^k < \left(\frac{1}{2B} + \frac{1}{b}\right)\left(Q_2^{\star} - Q_2^k\right)^2$ *since* $Q_2^k < Q_2^{\dagger k}$ *and* $Q_2^{\star} - Q_2^k > Q_2^{\dagger} - Q_2^{\dagger k}$. *We have shown that there is* $\Delta c > 0$ *such that* $\Pi^{\dagger k}(T) - \Pi^{\star}(T) > 0$ *for some* $\epsilon > 0$. *Now we want to show that* $\Pi^{\dagger k}(A) - \Pi^{\star}(A) \geq 0$ *for all* $A \geq \tilde{T}$ *with* $\tilde{T} < T$. *First, it is easy to show that* $\frac{\partial^2 \Pi^{\dagger k}(A) - \Pi^{\star}(A)}{\partial A^2} < 0$. *The desired result hence holds if* $\frac{\partial \Pi^{\dagger k}(A) - \Pi^{\star}(A)}{\partial A}|_{A=T} > 0$. *We have,*

$$
\begin{aligned}
\frac{\partial \Pi^{\dagger k}(A) - \Pi^{\star}(A)}{\partial A} &= \frac{\partial p_2^{\dagger k} Q_2^{\dagger k}}{\partial A} - \frac{\partial p_2^{\star} Q_2^{\star}}{\partial A} + \frac{\partial Q_2^{\star}}{\partial A}\frac{Q_1 + Q_2^{\star}}{B} - \frac{\partial Q_2^{\dagger k}}{\partial A}\frac{Q_1 - R + Q_2^{\dagger k}}{B} \\
&= p_2^{\dagger k} - \left(p_2^{\star}\frac{B}{2B+b} + Q_2^{\star}\frac{B+b}{b(2B+b)}\right) + \frac{B}{2B+b}\frac{Q_1 + Q_2^{\star}}{B} - \frac{Q_1 - R + Q_2^{\dagger k}}{B} \\
&= p_2^{\dagger k} - \frac{B}{2B+b}\left(p_2^{\star} - \frac{Q_2^{\star}}{b} - \frac{Q_1 + Q_2^{\star}}{B}\right) - \frac{Q_2^{\star}}{b} - \frac{Q_1 - R + Q_2^{\dagger k}}{B} \\
&= p_2^{\dagger k} - \frac{Q_2^{\star}}{b} - \frac{Q_1 - R + Q_2^{\dagger k}}{B} \\
&= \Delta c + \frac{k}{b} - \frac{Q_2^{\star}}{b} - \frac{Q_1 - R + Q_2^{\dagger k}}{B}.
\end{aligned} \tag{82}
$$

Furthermore, at $A = T$, *we have* $k = \epsilon + \frac{B+b}{2B+b}T - \frac{B}{2B+b}(Q_1 - R)$, *hence* $k/b = \epsilon/b + p_2^{\dagger}$.

Substituting into the above yields

$$\begin{aligned}
\frac{\partial \Pi^{\dagger k}(A) - \Pi^{\star}(A)}{\partial A}|_{A=T} &= \Delta c + \frac{\epsilon}{b} + p_2^{\dagger} - \frac{Q_2^{\star}}{b} - \frac{Q_1 - R + Q_2^{\dagger k}}{B} \\
&> \Delta c + \frac{\epsilon}{b} + p_2^{\star} - \frac{Q_2^{\star}}{b} - \frac{Q_1 - R + Q_2^{\dagger k}}{B} \\
&> \Delta c + \frac{\epsilon}{b} + p_2^{\star} - \frac{Q_2^{\star}}{b} - \frac{Q_1 + Q_2^{\star}}{B} \\
&> \Delta c + \frac{\epsilon}{b} \\
&> 0.
\end{aligned} \tag{83}$$

These results characterize the conditions that it is profitable to choose $R > 0$ *and trigger the step by changing output from* $Q_2^{\star}$ *to* $Q_2^{\dagger k}$*. It is interesting to note that when* $Q_2^{\star} > Q_2^{\dagger k}$ *the output is reduced when reneging occurs. This happens when* $\epsilon > \frac{B+b}{2B+b} R$*.*

B Data appendix & extra results

Table B1: Sample average of weather variables from 53 stations

Station	Lon	Lat	Temp	DewP	Humi	WindA	WindS
ABEE AGDM	-112.97	54.28	0.7	-4.2	73.4	19.8	10.8
ANDREW AGDM	-112.28	53.92	0.9	-3.7	75.2	20.1	13.1
BANFF CS	-115.55	51.19	1.9	-5.0	65.5	19.1	8.9
BARNWELL AGDM	-112.3	49.8	4.6	-1.9	67.6		17.1
BARONS AGCM	-113.22	50.03	3.7	-3.0	67.1		
BASSANO AGCM	-112.47	50.89	2.7	-3.1	71.1		15.1
BELLSHILL AGCM	-111.47	52.58	2.2	-3.4	71.1	20.6	15.6
BLOOD TRIBE AGDM	-113.05	49.57	4.2	-2.1	68.1		19.0
BOW ISLAND	-111.45	49.73	4.5	-2.1	66.8	20.7	15.7
BOW ISLAND IRRIGATI	-111.38	49.87	4.5	-1.8	68.7	20.0	13.2
BOW VALLEY	-115.07	51.08	3.3	-4.6	61.8		10.1
BROOKS	-111.85	50.56	3.5	-2.1	71.8		12.4
CADOGAN AGCM	-110.51	52.33	2.2	-3.6	70.6		
CAMROSE	-112.82	53.05	1.9			20.7	12.7
CRAIGMYLE AGCM	-112.25	51.78	2.2	-2.9	73.8		
DELBURNE AGCM	-113.18	52.18	2.6	-3.4	69.1		
DRUMHELLER EAST	-112.68	51.45	3.3	-3.1	68.2	20.4	9.5
EDMONTON BLATCHFORD	-113.52	53.57	3.2	-1.7	74.4		
EDMONTON CITY CENTR	-113.52	53.57	3.4	-3.6	63.7		12.6
EDMONTON INTERNATIO	-113.61	53.31	1.6				
ELK ISLAND NAT PARK	-112.87	53.68					6.5
ENCHANT AGDM	-112.43	50.18	3.8	-1.9	71.3	20.9	15.5
ESTHER 1	-110.21	51.67	2.5	-3.7	68.8		
ETZIKOM AGCM	-111.05	49.55	4.0				
GILT EDGE NORTH AGC	-110.62	53.07	1.8	-3.4	72.9		14.3
IRVINE AGCM	-110.26	49.99	4.6	-2.2	66.9		
JASPER WARDEN	-118.03	52.93	2.4	-4.2	67.5	17.8	6.9
KILLAM AGDM	-111.87	52.85	1.5	-4.3	69.8	21.0	14.4
KITSCOTY AGCM	-110.42	53.35	1.3	-3.5	74.3		
LETHBRIDGE CDA	-112.77	49.7	5.4	-2.1	63.4	21.0	16.1
LINDBERGH AGDM	-110.58	53.94	0.9	-4.2	72.6	19.9	11.2
LLOYDMINSTER A	-110.07	53.31	1.4	-3.8	72.2		16.1
MEDICINE HAT RCS	-110.72	50.03	4.6	-2.4	65.6		
MOSSLEIGH AGCM	-113.35	50.67	2.9	-3.1	69.6		
MUNDARE AGDM	-112.3	53.57	1.7	-3.8	71.0	21.1	13.5
NEW SAREPTA AGCM	-113.17	53.26	1.8	-4.0	69.5		
ONEFOUR CDA	-110.47	49.12	3.8			20.5	19.0
PAKOWKI LAKE AGCM	-111.13	49.22	4.2	-2.6	67.2		
POLLOCKVILLE AGDM	-111.71	51.13	2.2	-3.6	70.7		14.8
RED DEER A	-113.89	52.18	2.0	-4.0	67.6		9.8
RIVERCOURSE AGCM	-110.1	53.02	1.3	-4.0	72.2		
SMOKY LAKE AGDM	-112.5	54.28	1.1			19.2	11.6
STAVELY AAFC	-113.88	50.18	3.8	-4.3	60.0		16.2
SUNDRE A	-114.68	51.78	1.7	-5.0	66.4		6.7
THORSBY AGCM	-113.89	53.22	2.2	-3.7	68.6		
THREE HILLS	-113.21	51.77	2.7	-3.1	70.2		21.9
TOMAHAWK AGDM	-114.72	53.44	2.4	-3.5	69.2	20.0	9.8
TULLIBY LAKE AGCM	-110.08	53.66	0.9	-4.4	71.8		
VAUXHALL CDA CS	-112.13	50.05	4.2	-2.1	68.0		14.7
VIOLET GROVE CS	-115.13	53.14	2.8	-3.6	66.6		10.7
WAINWRIGHT CFB AIRF	-111.1	52.83	2.1				
WETASKIWIN AGCM	-113.44	52.98	1.8	-3.6	71.9		
WIMBORNE AGCM	-113.59	51.94	2.3	-3.8	68.7		

Notes: This table shows sample means of the weather variables used from each of the 53 stations. Temperature and Dew point temperature are Celsius degrees, humidity is in percentage points, wind angle is in tenths of degrees, wind speed in km/h.

Table B2: Model performance (Off-peak hours)

	Training set		Testing set		Reneging set		
n	7049		2820		450		
Parameters	316						
	S	RS	S	RS	S	RS	$\overline{RS}$
Mean Int. Bias	2.0	2.4	1.9	2.1	−7.8	−315.0	41.6
Mean Int. Abs. Bias	19.7	50.3	19.7	50.3	28.3	340.8	89.7
Mean Int. Rel. Abs. Bias	2.5%	0.8%	2.5%	0.8%	3.8%	5.0%	1.2%
RMISE	27.9	69.8	28.1	70.0	36.7	421.3	122.6
Rejection Rate (Imhof) H_0	–	–	0.045	0.057	0.120	1	0.382
Rejection Rate (BS) H_0	–	–	0.041	0.059	0.111	1	0.391
Zero parameters	122	80					
λ_{CV}	0.009	0.004					
Coverage probabilities	RS	$\hat{RS}$	RS	$\hat{RS}$	RS	$\hat{RS}$	$\overline{RS}$
Price	–	–	0.94	0.95	0.82	0.52	0.30
Output	–	–	0.94	0.94	0.81	0.75	0.80

Notes: This table shows statistics of model performance separately for the training set, testing set and reneging set. The reneging set includes all hours for days when reneging occurred. The statistics include Mean Integrated Bias, Absolute Bias, Relative Absolute Bias, the root-mean-integrated-squared-errors (RMISE), rejection rates using the asymptotic distribution (Imhof) and parametric bootstrap (BS). Zero parameters is the number of parameters set to zero by the algorithm (on average across the 52 price values). Inference for functions is described in Appendix C.

Price-responsive loads and net import functions We follow the methodology outlined in Ayres (2014), up to minor modifications due to data limitations, in order to incorporate price-responsive load and net import functions. We detail how it is done in our analysis below.

The equilibrium condition is

$$S(p) = D - RS(p) - nI(p) - S_{PRL}(p),$$

where the domestic production that we observe in each hour corresponds to $D - nI(P^\star) - S_{PRL}(P^\star)$, for the current price $P^\star$. We define the residual demand function as $RD(p) = (D - nI(P^\star) - S_{PRL}(P^\star)) - RS(p) - (nI(p) - nI(P^\star)) - (S_{PRL}(p) - S_{PRL}(P^\star))$ such that the equilibrium is always characterized by $S(P^\star) = RD(P^\star)$. Therefore, for any observed residual demand in the data where all we have is domestic production and residual supply bids like $RD_m(p) = (D - nI(P^\star) - S_{PRL}(P^\star)) - RS(p)$, we only need to substract the recentered net import and PRL supply functions to obtain the residual demand functions that account for price-responsive load and net import functions.

Following Ayres, we assume that the price-responsive load can be written as the supply function: $S_{PRL}(p < 100) = 31$, $S_{PRL}(100 \leq p < 500) = 93$, $S_{PRL}(500 \leq p < 800) = 139$, and $S_{PRL}(800 \leq p < 1000) = 180$. The net import function from British Columbia is $nI_{BC}(0 \leq p < 25) = -E_{CapBC}$,$nI_{BC}(25 \leq p < 27) = -0.75E_{CapBC}$, $nI_{BC}(27 \leq p < 29) = -0.5E_{CapBC}$, $nI_{BC}(29 \leq p < 33) = -0.25E_{CapBC}$, $nI_{BC}(33 \leq p < 45) = 0$, $nI_{BC}(45 \leq p < 46) = 0.25I_{CapBC}$, $nI_{BC}(46 \leq p < 55) = 0.5I_{CapBC}$, $nI_{BC}(55 \leq p < 89) = 0.75I_{CapBC}$, $nI_{BC}(89 \leq p < 1000) = I_{CapBC}$, where I_{CapBC} and E_{CapBC} denote the available import and export capacity to BC. The net import function from Saskatchewan is $nI_{SK}(0 \leq p < 25) = -E_{CapSK}$,$nI_{SK}(25 \leq p < 27) = -0.75E_{CapSK}$, $nI_{SK}(27 \leq p < 29) = -0.5E_{CapSK}$, $nI_{SK}(29 \leq p < 33) = -0.25E_{CapSK}$,$nI_{SK}(33 \leq p < 55) = 0$, $nI_{SK}(55 \leq p < 1000) = I_{CapSK}$, where I_{CapSK} and E_{CapSK} denote the available import and export capacity to SK.

Table B3: Model performance (PPA Plants)

	Training set		Testing set		Reneging set	
	Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak
SD5						
Mean Int. Bias	0.9	0.9	0.9	0.9	−108.2	−108.2
RIMSE	9.5	9.5	9.8	9.8	195.6	195.6
SD6						
Mean Int. Bias	0.5	0.5	0.5	0.5	−22.6	−22.6
RIMSE	10.1	10.1	9.8	9.8	88.1	88.1
KH1						
Mean Int. Bias	0.1	0.1	0.1	0.1	−21.5	−21.5
RIMSE	3.1	3.1	3.0	3.0	89.7	89.7
KH2						
Mean Int. Bias	0.1	0.1	0.1	0.1	−56.7	−56.7
RIMSE	3.2	3.2	3.1	3.1	145.8	145.8
SD2						
Mean Int. Bias	0.2	0.2	0.2	0.2	−21.3	−21.3
RIMSE	5.7	5.7	6.1	6.1	71.5	71.5
SD3						
Mean Int. Bias	0.6	0.6	0.5	0.5	−51.4	−51.4
RIMSE	9.5	9.5	10.0	10.0	125.7	125.7
SD4						
Mean Int. Bias	0.9	0.9	0.9	0.9	−83.8	−83.8
RIMSE	12.4	12.4	12.5	12.5	176.9	176.9

Notes: This table shows statistics of model performance for supply strategies of PPA plants which reneged. We report statistics separately for the training set, testing set, and reneging set. The reneging set includes all hours for days when reneging occurred. RMISE refer to the root-integrated-mean-squared-errors.

C Inference

We test the null hypothesis formalized in (17) using the Cramer-Von Mises statistic $CVM_S = \int_0^{1000} \widehat{\Delta S}_t(p)^2 dp$. Remark that $\widehat{\Delta S}_t(p) = \hat{u}_t(p)$ is obtained from the vector approximation $\boldsymbol{\hat{u}_t}$. This vector is asymptotically distributed as a multivariate normal. Thus, CVM_S asymptotically follows a weighted χ^2 distribution which weights depends on the eigenvalues of the asymptotic covariance of $\boldsymbol{\widehat{u}_t}$. We estimate this covariance matrix using the testing set (and not the training set). P-values are computed from an approximate asymptotic distribution.[61] The same approach is used to conduct inference on $\widehat{\Delta RD}_t$.

Besides, we test the null hypotheses

$$H_0 : \widehat{\Delta P}_t = 0, \text{ and,} \quad H_0 : \widehat{\Delta Q}_t = 0. \tag{84}$$

The distribution of those equilibrium values depends non-linearly on the joint distribution of supply and residual demand functions. We propose to use a parametric bootstrap to approximate their distributions. The random draws are taken from the multivariate normal distribution using the covariance of error vectors for supply and residual demand (estimated using the testing set). This aims at accounting for the correlation between the two functions. The procedure is as follows. Separately for each hour t in the sample, we draw 10,000 multivariate normal random vectors $\boldsymbol{u_t^{S_b}}$ and $\boldsymbol{u_t^{RD_b}}$ to construct $\widehat{S}_t^{\star b}$ and $\widehat{RD}_t^{\star b}$. Then, for each draw we compute the equilibrium price and firm's output $(\hat{P}_t^b, \hat{Q}_t^{\star b})$. Finally, we use the quantiles of the bootstrapped distribution to construct confidence intervals and to compute p-values for the CVM statistics.

[61] A more formal treatment of functional testing procedures is proposed in Benatia (2018*b*) and Carrasco, Florens and Renault (2014).