"Climate Policy and Border Measures:

The Case of the US Aluminum Industry" *

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Abstract

In this paper, the impact of border measures for climate policy on carbon leakage, and competitiveness of US aluminum producers is analyzed. An appropriate border measure is shown to depend on competition in aluminum production, as well as the basis for assessing trade neutrality of a border measure. If neutrality is based on market volume, carbon leakage is prevented, but competitiveness cannot be maintained. If neutrality is based on market share, competitiveness can be maintained and there is negative carbon leakage. In either case, users of aluminum incur deadweight losses from the combination of climate policy and border measures.

Keywords: climate policy, carbon leakage, border measures, aluminum

JEL Codes: H87, Q38

Introduction

In the past decade, it has become increasingly obvious that even though negotiation of the Kyoto Protocol on Global Climate Change in 1997 was a useful first step, further efforts to develop a comprehensive multilateral agreement for reducing carbon emissions will be necessary if global climate change is to be properly addressed. However, successive failures of the United Nations Climate Change Conference suggest that hopes of reaching agreement by 2015 on the setting of emissions caps after 2020 are optimistic at best (Helm, Hepburn, and Rutta 2012). Irrespective of the economic logic supporting a multilateral approach to dealing with a global public bad, there has been a shift in many countries from pursuing a legally binding international agreement to one where individual countries decide on their own emission reduction targets and the policy instrument for reaching that target.

Much of the recent discussion as well as actual application of climate policy has focused on the use of market-based instruments such as carbon taxes and tradable emissions permits. Carbon taxes have been proposed in many countries, including China, and either are or have been applied in several countries, most notably Australia. In the case of the current European Emissions Trading Scheme, Canadian provinces such as Québec, and also previously proposed US climate policy legislation, the choice of instrument is a system of tradable permits or what is usually referred to as cap-and-trade.

Whether a carbon tax or cap-and-trade system is used, the expectation is that certain energy-intensive industries downstream from electricity production such as iron and steel, aluminum, chemicals, paper and cement production, will all face increased costs of production. As a consequence, much of the unilateral climate legislation that has been proposed also includes some type of border measure to be targeted at energy-intensive imports. The inclusion of border measures in climate change legislation is predicated on two concerns: first, there will be *carbon leakage*, i.e., production by energy-intensive industries will be shifted to countries with less restrictive climate policies; second, there will be a reduction in *competitiveness* of producers in industries most affected by domestic climate policies (WTO/UNEP 2009).

There has been analysis of how trade policy instruments might be used to prevent carbon leakage when one group of countries commits to cooperation over climate policy, while a second group free-rides by not implementing climate policy. For example, Hoel (1996) shows that a social optimum can be obtained if countries that form a coalition set common carbon taxes, and at the same time use import tariffs (export subsidies) on all energy-intensive traded goods, the objective being to shift the terms of trade against free-riding countries, thereby reducing carbon leakage.

While the argument that using trade policy instruments to resolve a market failure is compelling theoretically, it has raised practical concerns that border tariffs could be used for protectionist ends and would therefore be constrained by current WTO/GATT rules (Holmes, Reilly and Rollo 2012). However, if such trade policy instruments are treated as *border tax adjustments* (BTAs) rather than border taxes (subsidies), the principle for their use in the presence of a domestically imposed excise tax is well-founded in the international public finance literature on *origin* vs. *destination-based* taxation systems (Lockwood and Whalley 2010).

Essentially this principle is captured in the WTO/GATT rules: GATT Article II: 2(a) allows members of the WTO to place on the imports of any good, a BTA equivalent to an internal tax on the like good. However, under GATT Article III: 2, the BTA cannot be applied *in excess* of that applied directly or indirectly to the like domestic good, i.e., they have to be *neutral* in terms of their impact on trade, their objective being to preserve *competitive equality* between domestic and imported goods (WTO 1997). In addition, with respect to exported goods, WTO/GATT rules allow rebate of the domestic tax on the exported good, as long as the border adjustment does not exceed the level of the domestic tax, it is not regarded as an export subsidy under the GATT Subsidies Code.

While there has been considerable discussion about the legal permissibility of BTAs for domestic climate policy, two key aspects of the legal debate remain unresolved (Pauwelyn 2007). First it is unclear whether a BTA will be allowed on imports of a final energy-intensive good such as aluminum, when the domestic carbon tax directly affects an input into its production such as electricity, which is not physically present in the final good. Pauwelyn argues convincingly that if the objective of a carbon tax on electricity production is to ensure that the price domestic consumers pay for an energy-intensive product such as aluminum reflects the social cost of producing aluminum, then a BTA on imported aluminum should be permitted.

Second, it is also unclear whether WTO rules on BTAs would apply in the case where domestic climate policy consists of a cap-and-trade system. Here Pauwelyn argues that if emission credits command a market price, then the obligation of electricity producers to hold emission credits up to the actual level of their carbon emissions qualifies as an internal tax. Assuming this internal tax is passed forward to domestic aluminum producers/consumers, an appropriate BTA can be implemented on imports of aluminum. In light of this discussion, this paper proceeds upon the assumption that a BTA for either a domestic carbon tax or cap-and-trade system will be considered legal.

While carbon leakage and competitiveness are closely connected in the climate policy debate, the latter is a rather more difficult concept to define. Typically, it would be thought of in terms of market share and/or the profit of producers, which in turn are a function of the specific characteristics of an industry subject to domestic climate policy, including factors such as market structure, industry technology and the nature of competition between producers. In the case of perfectly competitive markets, producers make zero economic profits in long-run equilibrium. Consequently, if producers and policymakers are concerned about the effect of unilateral implementation of climate policy on competitiveness as defined above, markets would have to be imperfectly competitive with producers having non-trivial market shares and earning positive economic profits in equilibrium. This suggests that climate policy and BTAs are perhaps best analyzed in the context of the literature on trade and environmental policy pioneered by, *inter alia*, Conrad (1993). The key point of this previous literature is that if producers earn positive economic profits, implementation of climate policy may have the effect of shifting profits between domestic and foreign producers, thereby affecting the former's competitiveness.

Houser *et al*. (2009) identify five energy-intensive industries in the US most likely to be affected by unilateral climate policy: steel, aluminum, chemicals, paper and cement. Several authors analyzing the carbon leakage/competitiveness issue have already modeled firm behavior in these industries as imperfectly competitive, for example, see Smale *et al*.'s (2006) analysis of steel, paper and cement production. In the case of US aluminum production, the industry has repeatedly been investigated by the antitrust authorities for anti-competitive behavior, and there is empirical evidence that producers in the sector do behave less than competitively (Yang 2005).

Given this background, in this paper the potential effects of climate policy on the US aluminum industry are evaluated, based on a simple model that can be calibrated to capture industry market structure and behavior. This analysis generates two key results: first, characterizing behavior in the US aluminum industry as imperfectly competitive captures the link between carbon leakage and competitiveness. Importantly, the extent to which climate policy results in carbon leakage and a loss of competitiveness by US aluminum producers depends on how aggressively competing Canadian aluminum producers respond to the formers' output changes. Second, the results illustrate a classic regulatory problem: the difficulty of achieving several policy objectives (ensuring no carbon leakage/maintaining competitiveness) with a limited set of policy instruments (climate policy, BTAs), in a situation where there is a binding external constraint (WTO/GATT rules) on the use of one of those instruments (BTAs).

The paper is organized as follows: first, key characteristics of the US aluminum industry are described; second a model of the aluminum production sector is outlined; third, climate policy and BTAs are discussed; fourth, the results of simulating the effects of BTAs are presented; and finally, a summary of the paper and some conclusions are presented.

The US Aluminum Industry

As previously noted, the US aluminum industry has already been identified as one that might be vulnerable to the issues of competitiveness and carbon leakage, due to the fact that it is both energy-intensive and also highly exposed to international competition (Houser *et al*. 2009). In describing the industry, the technology of production and market structure are briefly discussed.

Technology of production

Aluminum production is part of a vertical production process that initially requires the raw materials bauxite and alumina. Bauxite is mined in 26 countries around the world, with 83% of the world's production being accounted for by Australia, Brazil, China, India and Guinea in 2011 (US Geological Survey 2012). Bauxite is processed into alumina, which is subsequently used to produce aluminum. Unwrought aluminum is then cast into various shapes depending on its end use: large flat ingots are intended for hot-rolling to produce aluminum plate and sheet, while cylindrical ingots are for extrusion through a die to produce tubing and other hollow shapes.

Aluminum is extracted from alumina using an electrolytic reduction method known as the Hall-Héroult process. It takes place in a series of steel-shelled cells, or "pots", which are lined with refractory bricks and carbon blocks, alumina being dissolved in the pot using a molten electrolyte. An electrical current is passed through the electrolyte via a carbon anode hung over the pots, the latter acting as a cathode, reducing the alumina to aluminum and oxygen. The oxygen is released on the carbon anode where it forms carbon monoxide and carbon dioxide, while the aluminum settles to the bottom of the pots. This process is very energy-intensive, with anywhere from 14 to 17 megawatts of electricity required per tonne of aluminum, the amount depending on the type of anode-technology used (prebake vs. Söderberg). Production costs for primary aluminum are dominated by raw materials (35%), electricity (25%), and anodes (16%) respectively, the remainder being due to labor and other input costs (24%), (USITC 2010).

In terms of environmental impact, the production process has two key sources for carbon and other greenhouse gas (GHG) emissions: first, there are direct carbon dioxide emissions due to anode degradation and perfluorocarbon (PFC) emissions from the electrolyte, amounting to emissions of 2-3 tCO_2/t of aluminum produced (Carbon Trust 2011); second, there are indirect carbon emissions associated with upstream electricity production, where the amount of carbon dioxide produced depends on the method of electricity generation, ranging from 3 tCO_2/t of aluminum for hydro-electric production to 20 tCO_2/t of aluminum for coal-powered production (Carbon Trust).

Market Structure

The most complete data for market structure of the aluminum industry is for 2008. With respect to the US, table 1 indicates that market structure is highly concentrated with two producers, Alcoa and Century Aluminum, accounting for 73% of production capacity. Based on *s* being the share of production of each firm, the Herfindahl index $H = \sum s^2$ = 0.34, which when calculated as a numbers-equivalent, $1/H$ = 2.94 implies a market structure of almost 3 symmetric-sized producers. This market structure is a function of high entry barriers due to the size of investment required in production facilities, and also the extent to which merger activity over the period 2004-08 resulted in industry consolidation (USITC 2010). Despite this concentrated market structure, there is significant import competition in the US market. In 2008, US production of aluminum was 2.66 million tonnes, which was almost exclusively for domestic consumption. Total imports of aluminum were 2.81 million tonnes, of which over 71% was accounted for by Canada, the other major suppliers being Russia and Venezuela with 10% and 4% shares of US imports respectively (USITC 2010).

Canada's share of US aluminum imports increased substantially after 2004, such that by 2008, Canadian exports to the US accounted for 64% of its total production (USITC, 2010), suggesting that it is reasonable to think of the US and Canada as a well-defined North American market where Canadian producers essentially compete in the US market. In terms of market structure in Canada, table 1 indicates that the aluminum industry there is also is highly concentrated, with two producers, Rio Tinto Alcan and Alcoa, accounting for 82% of production capacity in 2008 (Natural Resources Canada 2009). The Herfindahl index H = 0.38, giving a numbers equivalent of $1/H$ = 2.57, implying a slightly more concentrated market in Canada of 2.5 symmetric-sized producers. It should also be noted from table 1 that both the US and Canadian industries are characterized by the operations of multinational producers, Alcoa and Rio Tinto Alcan, who between them account for 24% of the world's aluminum production (Carbon Trust). These producers operate in both the US and Canada, although Alcoa clearly has more market share in Canada than Rio Tinto Alcan does in the US.

A key difference between the US and Canadian aluminum industries is that while geographic location of smelting plants in both countries is tied directly to the availability and cost of electricity, the Canadian industry is located predominantly in the province of Québec, where electricity is produced entirely from hydro-electric sources (Natural Resources Canada). By contrast, US smelting plants are located in the southeastern region (South Carolina, Kentucky, and Virginia), the Midwest (Indiana, Missouri, and Ohio), New York, and the Pacific Northwest (Washington, and Montana), where the lion's share of electricity generation is fossil fuel-based (USITC 2010; USEIA 2012). This of course has important implications for carbon emissions from aluminum production in the US as compared to Canada, where the former generates an estimated 7.4 tCO_2/t of aluminum (Carbon Trust), while the latter generates an estimated 2.5 tCO_2/t of aluminum (CIEEDAC 2013).

A Model of the US Aluminum Industry

The model of the US aluminum industry presented here is a linear version of McCorriston and Sheldon (2005) that is easily calibrated to available data for the US aluminum industry and then used for policy simulation. (See associated Appendix containing a complete outline of the model and how to calibrate it.) The structure of the North American aluminum industry is divided into two, where subscript 1 refers to US aluminum producers and subscript 2 refers to Canadian-based producers exporting to the US market. It is assumed that there is no entry/exit of producers who face constant average and marginal operating costs. While it is possible for producers with plants in both the US and Canada to switch production between the two countries, this is not modeled explicitly.

In each country, production of aluminum generates carbon emissions e via the function, $e_i = f(Q_i)$ where Q_i is total aluminum production in countries i =1, 2, and emissions are the sum of direct emissions from aluminum production and indirect emissions due to upstream production of the key input electricity. Also, $f'(Q_i) > 0$, i.e., GHG emissions (direct and indirect) increase in aluminum output, and it is possible that $f'(Q_1) \neq f'(Q_2)$, capturing the idea that aluminum production in the US may generate more or less carbon emissions for a given level of output as compared to aluminum production in Canada.

Demand

The inverse derived demand functions for aluminum are given as:

$$p_1 = a_1 - b_1 Q_1 - kQ_2 \tag{1}$$

$$p_2 = a_2 - kQ_1 - b_2 Q_2, \tag{2}$$

p_1 and p_2 are US and Canadian aluminum prices respectively, all parameters are positive, and $b_1 b_2 - k^2 \geq 0$, allowing US and Canadian aluminum to be imperfect substitutes.

Producer behavior

On the supply side, the profit functions of typical US and Canadian aluminum producers are:

$$\pi_1 = (p_1 - c_1)q_1 \tag{3}$$

$$\pi_2 = (p_2 - c_2)q_2, \tag{4}$$

where q_i and c_i are their output and costs respectively.

If producers maximize profits with respect to output, the aggregate first-order conditions for n_1(n_2) symmetric US(Canadian) producers are:

$$p_1 - c_1 - Q_1\lambda_1 = 0 \tag{5}$$

$$p_2 - c_2 - Q_2\lambda_2 = 0, \tag{6}$$

where the λs measures the mark-up of price over marginal cost by US and Canadian firms. With the relevant data, values for the λs can be retrieved from (5) and (6), and then compared to the well-known market structures of competition, $\lambda = 0$, and Cournot, $\lambda = b/n$.

Market equilibrium for the US aluminum industry is derived as:

$$\begin{bmatrix} dQ_1 \\ dQ_2 \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} (b_2+\lambda_2) & -k \\ -k & (b_1+\lambda_1) \end{bmatrix}\begin{bmatrix} -dc_1 \\ -dc_2 \end{bmatrix}, \tag{7}$$

where $\Delta = \{(b_1+\lambda_1)(b_2+\lambda_2) - k^2\} > 0$.

Climate Policy and Border Tax Adjustments

Climate policy and leakage

Assume initially that BTAs are not available, so that the US government can only target climate policy at its electricity and aluminum producers. To keep the exposition simple, the price associated with emitting carbon or any other GHGs, is denoted as g^e, which is based on either a carbon tax t^e, or the market price of an emissions permit m^e, and it is assumed $g^e = t^e = m^e$. Setting a carbon price raises US aluminum producers' costs c_1 via two channels: indirectly through the price of carbon being transmitted into higher electricity prices and directly through aluminum producers being faced with a carbon price. This increase in costs affects the output of US aluminum producers, given by dQ_1/dc_1. The cost increase to US aluminum producers also affects imports of Canadian aluminum, given by dQ_2/dc_1. Following Ritz's (2009) specification of carbon leakage, and assuming that US electricity aluminum producers do not respond to a carbon price by reducing their intensity of carbon emissions via cleaner technology, carbon leakage *l* is given as:

$$l = \frac{de_2}{-de_1} \equiv \left[\frac{f'(Q_2)}{f'(Q_1)}.\frac{dQ_2}{-dQ_1}\right], \tag{8}$$

i.e., even if intensity of carbon emissions is the same in US and Canadian aluminum production, $f'(Q_1) = f'(Q_2)$, there will be positive carbon leakage, l >0, if there is positive output leakage, i.e., $dQ_2 / -dQ_1 > 0$. Equation (7) can be used to re-write (8) explicitly as:

$$l = \frac{de_2}{-de_1} \equiv \left[\frac{f'(Q_2)}{f'(Q_1)} . \frac{\Delta^{-1} k dc_1}{-\{\Delta^{-1}(b_2 + \lambda_2) dc_1\}} \right]. \qquad (9)$$

If l > 0, there is positive carbon leakage, and if l < 0, there is negative carbon leakage in the sense that carbon emissions actually decrease after implementation of US carbon pricing. Given that a US carbon price has a positive effect on imports of Canadian aluminum, $dQ_2 = \Delta^{-1} k dc_1 > 0$, and a negative effect on US aluminum production, $dQ_1 = \{\Delta^{-1}(b_2 + \lambda_2) dc_1\} < 0$, the direction of carbon leakage is given by $f'(Q_2)$ relative to $f'(Q_1)$, and the magnitude of the output response by US and Canadian aluminum producers.

Border tax adjustments and neutrality

Now assume a BTA, t^b, can be targeted at US imports of aluminum, thereby raising the costs of Canadian producers. This is given by dQ_2 / dc_2, which in turn affects Canadian carbon emissions e_2, and thereby carbon leakage l. Since the WTO/GATT guidelines on BTAs are not specific in defining 'competitive equality', two cases are considered where the neutral BTA is defined as *either* the change in c_2 that keeps the *volume* of imports of Canadian aluminum constant given a carbon price g^e, *or* as the change in c_2 that keeps the US *market share* of imports of Canadian aluminum constant given g^e.

It can be argued that both of these rules fit into a broader rationale, on how implementation of stricter environmental standards can be accommodated in a manner that is consistent with key principles of the WTO/GATT concerning market access. In the absence of BTAs, the US would have little incentive to unilaterally implement carbon pricing due to the competitiveness effect. However, if the competitiveness effect is thought of in terms of Canadian producers gaining additional market access to the US aluminum market beyond levels previously negotiated in WTO/GATT, using a BTA to restore the level of market access to its negotiated level, after implementation of the environmental standard, would be unlikely to elicit a complaint to the WTO from Canada.

If neutrality is defined in terms of import volume, the appropriate BTA is given as:

$$t^e = \frac{(dQ_2 / dc_1)g^e}{-(dQ_2 / dc_2)} = \frac{\Delta^{-1}(k)g^e}{\Delta^{-1}(b_1 + \lambda_1)} \qquad (10)$$

When markets are perfectly competitive, $\lambda_1 = 0$ and $k = b_1$, the reduction in US imports of Canadian aluminum due to the BTA will exactly offset the increase in US imports of Canadian aluminum due to carbon pricing, i.e., $|dQ_2 / dc_2| = |dQ_2 / dc_1|$, the net effect of policies being $dQ_2 = 0$. Therefore, the appropriate BTA should be set equal to the US carbon price. Specifically, with a carbon price of g^e, the BTA is based on carbon embodied in the domestically produced final good, not the carbon intensity of imported aluminum.

In contrast, when markets are imperfectly competitive, $\lambda_1 > 0$ and $k \le b_1$, setting the BTA equal to the price of carbon will lead to a non-neutral outcome - $dQ_2 \ne 0$. The BTA reduces the level of US imports of Canadian aluminum, i.e., $dQ_2 / dc_2 = \Delta^{-1}(b_1 + \lambda_1) < 0$, and US carbon pricing increases the level of US imports of aluminum i.e., $dQ_2 / dc_1 = \Delta^{-1}k > 0$. However, the absolute value of the own-effect of a BTA on Canadian producers is greater than the cross-effect of US carbon pricing on Canadian producers, i.e., $|dQ_2 / dc_2| > |dQ_2 / dc_1|$. Therefore, to ensure trade neutrality, the BTA should be set less than the carbon price.

In the case of import-share neutrality, the appropriate BTA is defined as one where the net effect of the carbon price on Q_1 and Q_2 must equal the net effect of the BTA on Q_1 and Q_2. In this case, the neutral BTA is defined as:

$$t^b = \frac{[(dQ_2 / dc_1) + (dQ_1 / dc_1)]g^e}{[(dQ_1 / dc_2) + (dQ_2 / dc_2)]} = \frac{[\Delta^{-1}\{k + (b_2 + \lambda_2)\}]g^e}{[\Delta^{-1}\{k + (b_1 + \lambda_1)\}]}. \tag{11}$$

Under perfect competition, $\lambda_i = 0$ and $k = b_1 = b_2$, and therefore, the effect of policies is one where the net response of US and Canadian aluminum producers to the carbon price is matched exactly by their net response to the BTA, i.e., the numerator in (11) is equal to the denominator, resulting in no change in the US market share of imports of Canadian aluminum, $d(Q_2 / (Q_1 + Q_2) = 0$. In other words, the BTA should again be set equal to the US carbon price. With imperfect competition, the magnitude of the BTA relative to the US carbon price is dependent on the extent of imperfect competition in the US aluminum industry, as captured in λ, and also the relative size of the own-effects to the cross-effect of policies. In particular, if the expression inside square brackets in the numerator of (11) is greater than the denominator, the BTA will be set above the US carbon price in order to satisfy trade neutrality.

Model Calibration and Policy Simulation

Calibration

Given the theoretical structure, the demand system is calibrated for 2008, the year of most recent and complete data for the US and Canadian aluminum industries, using price, quantity, and elasticity data as presented in table 2. p_1 and p_2 are based on the unit values of US-produced and imported aluminum as reported by the US Geological Survey (2010) and the USITC (2010) respectively, while Q_1 and Q_2 are derived from USITC (2010) data. The value of the elasticity of demand is based on an econometric estimate by Yang (2005), and the elasticity of substitution between US-produced and imported aluminium is based on an estimate reported by USITC (2004). The values for c_1 and c_2 are based on production cost estimates for North America reported by the Carbon Trust (2011). Based on model calibration, the parameters for the inverse demand functions consistent with equilibrium in the US aluminium industry in 2008 are shown in the top half of table 3. The market power parameters λ_i are also presented in the bottom half of table 3, the values indicating that aluminum producers were behaving more competitively than Cournot in 2008.

Policy Simulation

In simulating the effects of US carbon pricing and BTAs, the US social welfare function is defined as:

$$W = \pi_1 + \Gamma_1 + g^e\{f'(Q_1)\}Q_1 + t^b Q_2 - d(e_1 + e_2)\,, \qquad (12)$$

where the first term denotes the profits of US aluminum producers, the second term is the surplus of US aluminum users, the third term is the potential revenue raised from carbon pricing, the fourth term is tax revenue raised from a BTA, and the final term is the sum of the damage from carbon emissions in both countries, bearing in mind that carbon emissions are being treated as a global public bad. The latter are evaluated based on assuming that at a discount rate of 3%, the social cost of CO_2 in 2050 released in 2008 is equal to \$21/t (IWGSCC 2010).

The initial policy simulation focuses on the effect of a US carbon price set at \$25/t CO_2, and borne by both, US electricity and aluminum producers. This carbon price is based on Tol's (2005) mean CO_2 damage estimate, and also matches up with Fowlie's (2009) analysis of carbon pricing in the Californian electricity sector. Importantly, the US carbon price is assumed to be set higher than that recently introduced in Canada, i.e., carbon leakage and competitiveness effects will be driven by differential carbon pricing. Starting January 1, 2013, Québec has implemented a cap-and-trade system for carbon emission permits as part of the Western Climate Initiative (O'Brien *et al*. 2013). The program covers electricity generation and industrial sectors with annual GHG emissions of over 25,000 tonnes, which includes aluminum production. From the start of the program, distribution of emissions permits to electricity generation has been set at 100% via auction, but because of concerns about competitiveness and carbon leakage, industries such as aluminum received 80-100% of their required emissions permits free of charge up to 2014, after which the number of free emissions permits they receive declines by 1-2% per year. The Québec Ministry of Sustainable Development, Environment, Wildlife and Parks (MDDEFP) held permit auctions on December 3, 2013 and March 4, 2014, where the final auction prices averaged \$10.2/t CO_2 (MDDEFP 2013; 2014).

In order to evaluate the impact of carbon pricing on US aluminum producers due to their indirect emissions via electricity generation, the expected change in US electricity prices is calculated, based on Fowlie. Assuming the electricity industry is characterized by Cournot behavior, she forecasts that carbon pricing raises the price of electricity by \$22.87/MWh, an increase of 49%, and implying pass-through of the carbon price of 91%. Given that electricity accounts for 25% of US aluminum production costs, this translates into an increase in c_1 by \$220/t of aluminum produced. In terms of direct carbon emissions from US aluminum production, the impact of carbon pricing is calculated to increase c_1 by \$62.5/t of aluminum produced, based on emissions of 2.5 tCO_2/t of aluminum. This implies a total increase in the costs facing US aluminum producers of \$282/t of aluminum produced.

The auction prices for carbon permits in Canada are borne directly by Québec electricity producers, and then passed on to Canadian aluminum producers, who as noted earlier, are almost exclusively located in Québec. Assuming the rate of pass-through of increased electricity prices is similar in Canada to the US, Québec carbon pricing translates into an increase in Canadian aluminum production costs c_2 by $84/t of aluminum produced. The initial free allocation of emissions permits, to aluminum producers in Québec means that there is no direct increase in Canadian aluminum production costs.

The results of simulating introduction of a US carbon price are reported in table 4. Column (1) reports the breakdown of social welfare pre-implementation of any US carbon pricing, given Canadian carbon pricing is already in place, along with the level of carbon emissions and the market share of US aluminum producers. This can then be compared to the effects of implementing differential US and Canadian carbon pricing in column (2) of the table. The results indicate that the policy generates a 3.7% decline in US social welfare, with the 15.5% decline in profits of US aluminum producers, and the 5.3% decline in surplus of US aluminum users being partially offset by the tax revenue raised from carbon pricing and the reduction in the social cost of emissions. In terms of competitiveness and carbon leakage, the results indicate US aluminum producers lose market share and there is positive carbon leakage, although total North American GHG emissions do decline by 5.6%.

The net deadweight loss of imposing a carbon price in the presence of imperfectly competitive behavior is also derived: gross deadweight loss is calculated as the difference between the lost surplus of US aluminum users due to higher aluminum prices, and the tax revenue raised from carbon pricing, and from this reduction in the social cost of carbon emissions is deducted. The results indicate that there is net deadweight loss of -$0.14 billion, which highlights a result discussed in detail by Conrad (1993): in the presence of imperfect competition, there is a tradeoff between targeting a policy instrument at one market failure (a global public bad) in the presence of a second market failure (market power). The implication is that in a second-best setting, the carbon price may have to be lower in order to minimize the net deadweight loss.

Sensitivity analysis is also conducted for introduction of a US carbon price, consisting of reductions in the elasticity of demand, the elasticity of substitution, and the discount rate. The latter is reduced to 2.5% the social cost of CO_2 in 2050 released in 2008 increasing to $35/t (IWGSCC 2010). The results of the sensitivity analysis are shown in table 5. Column (1) reports the breakdown of pre-policy social welfare, along with the level of carbon emissions and the market share of US aluminum producers. The key changes compared to the results reported in table 4 are an increase in the initial level of user surplus of US aluminum users due to reduction in the elasticity of demand, along with higher social costs of emissions due to the reduction in the discount rate, the net effect being higher pre-policy social welfare. Again, this can be compared to the effects of implementing differential US and Canadian carbon pricing in column (2) of the table. The key results to note are that there is a lower decline in US social welfare of 2.6%, and a slightly lower level of carbon leakage, driven by the combination of lower elasticities of demand and substitution. However, the net deadweight losses are unaffected, higher user surplus being offset by higher social costs of emissions.

The second policy simulation analyzes the effect of implementation in the US of a carbon price in combination with a BTA set by the US on imports of Canadian aluminum. As before the carbon price is set at $25/t CO_2 borne by both US electricity and aluminum producers, and a $10.2/t CO_2 carbon price borne by Canadian electricity producers and passed on to aluminum producers in Québec, and Canadian aluminum producers are assumed to receive free emissions permits. In the case of a BTA designed to ensure that the volume of Canadian aluminum imports does not change after implementation of the carbon price, equation (10) indicates it should be set at \$141/t of aluminum imported, i.e., $t^b < g^e$. In the case of a BTA designed to ensure that the market share of imports does not change after implementation of the carbon price, equation (11) indicates it should be set at \$469/t of aluminum imported, i.e., $t^b > g^e$.

The results of implementing either one of these BTAs are shown in columns (3) and (4) of table 4. In the case of the volume BTA, the results indicate that compared to the US setting a carbon price alone, the joint policy generates a lower decline in social welfare of 2.3% relative to the pre-policy benchmark. The 12.7% decline in profits and 7.2% decline in surplus of US aluminum producers and users respectively are partially offset by the tax revenue raised from carbon pricing and the BTA, along with a reduction in the social cost of emissions. In terms of competitiveness and carbon leakage, the results indicate US aluminum producers still lose some market share, but there is no carbon leakage, i.e., the competitiveness problem of US implementation of a differential carbon price relative to Canada cannot be wholly resolved with a volume BTA. The results also indicate that there is a smaller net deadweight loss of -\$0.09 billion due to the fact that there are now two policy instruments available. However, as the results in table 5, column (3) indicate, sensitivity analysis for the effects of a volume BTA results in a larger net deadweight loss of -\$0.11 billion, driven by lower tax revenue. The latter is almost entirely due to the effect of reducing the elasticity of substitution between US produced aluminum and imports from Canada, resulting in a lower BTA being required to maintain neutrality.

In the case of the share BTA, the results indicate that compared to the US setting carbon prices alone, the joint policy generates a lower decline in social welfare of 1.3% relative to the pre-policy benchmark. Again, the 6.0% decline in profits and the 11.6% decline in surplus of US aluminum producers and users respectively, are partially offset by the tax revenue raised from carbon pricing and the BTA, along with a reduction in the social cost of emissions. In terms of competitiveness, the results indicate that US aluminum producers no longer lose market share, a function of Canadian producers maintaining their market share. Interestingly, there is also negative carbon leakage, which follows from the combination of the US carbon tax and share BTA, reducing the output of both US and Canadian producers, but at the same time maintaining their pre-policy market shares. In other words, this particular policy combination actually "facilitates collusion" among US and Canadian aluminum producers, generating the largest reduction in user surplus of any policy combination. Again this highlights the second-best nature of the problem: while targeting carbon emissions reduces emissions, thereby lowering social cost, and use of a BTA maintains competitiveness and prevents carbon leakage, another market failure, exertion of market power, is exacerbated along with the associated deadweight loss from oligopoly. The direction of these results is confirmed in the sensitivity analysis shown in table 5, column (4), although there is a larger increase in net deadweight loss of -$0.06 billion, and negative carbon leakage is lower due to reduction of the elasticities of demand and substitution.

5. Summary and Conclusions

The analysis presented in this paper is motivated by the fact that proposed climate legislation often includes some type of border measure to be targeted at energy-intensive imports. The argument for including such measures is not only the possibility that import-competing producers will become less competitive following unilateral implementation of domestic climate policy, but that there will be carbon leakage as market share shifts to foreign producers. In this context, the main contribution of this paper is analysis of the impact of climate policy and border measures in a setting that reasonably characterizes the industrial organization of an import-competing energy-intensive sector such as aluminum production. Once imperfect competition is allowed for in US aluminum production, competitiveness can be defined in terms of profit-shifting between US and Canadian producers. Importantly, the extent of carbon leakage and reduction in competitiveness are both shown to be dependent on the extent of imperfect competition in aluminum production, and hence on how producers interact with each other in the presence of policies that affect their costs of production.

Assuming that WTO/GATT rules on border tax adjustments apply in the context of carbon pricing borne by producers of a good such as aluminum that contributes both direct and indirect carbon emissions, the key consideration in the paper is whether such adjustments will jointly resolve the issues of carbon leakage and loss of competitiveness by US producers of aluminum. Importantly, if WTO/GATT rules on border tax adjustments are based on maintaining the volume of aluminum imports, there will be no carbon leakage, US producers incurring a reduction in output and lost profits and hence their competitiveness. Alternatively, if WTO/GATT rules on border tax adjustments are interpreted in terms of maintaining the US market share of aluminum imports, global carbon emissions are actually reduced due to there being negative carbon leakage, and the competitiveness of US producers is maintained.

It should also be noted that in both interpretations of WTO/GATT rules on border tax adjustments, users of aluminum actually suffer a deadweight loss due to aggregate output of aluminum being reduced in an imperfectly competitive setting. This highlights an important practical tension between targeting an environmental market failure in the presence of a second market failure, market power. This tension is greatest in the case of a BTA based on maintaining the US market share of imports, given that the BTA has to be set much higher than the US carbon price in order to maintain the competitiveness of US aluminum producers.

However, even if domestic political economy concerns favor the market share over the market volume interpretation of WTO/GATT rules, the former would seem much more likely to fall foul of the national treatment principle contained in Article III of GATT. Specifically, even if trade neutrality is maintained, Canadian exporters of aluminum might contest that they are being discriminated against via a BTA that is higher than the effective carbon price faced by US aluminum producers.

Appendix: Model Derivation and Calibration

The aggregate derived demand functions for aluminum are given as:

$$Q_1 = A_1 - B_1 p_1 + K p_2 \tag{A1}$$

$$Q_2 = A_2 - K p_1 + B_2 p_2 , \tag{A2}$$

where all parameters are positive, $(B_1 B_2 - K^2 \geq 0)$, and p_1 and p_2 are prices. The corresponding inverse derived demand functions are:

$$p_1 = a_1 - b_1 Q_1 - k Q_2 \tag{A3}$$

$$p_2 = a_2 - k Q_1 - b_2 Q_2 , \tag{A4}$$

where all parameters are positive and $b_1 b_2 - k^2 \geq 0$.

This demand system can be derived by maximizing the following aggregate profits function for downstream producers that use aluminum in the US as an intermediate input:

$$\Gamma_1 = f(Q_1, Q_2) - p_1 Q_1 - p_2 Q_2 , \tag{A5}$$

where the aggregate production function $f(Q_1, Q_2)$ is defined as:

$$f(Q_1, Q_2) = a_1 Q_1 + a_2 Q_2 - 0.5\left(b_1 Q_1^2 + b_2 Q_2^2 + 2k Q_1 Q_2\right). \tag{A6}$$

It is important to note that, for simplicity, the aggregate production function is of quadratic form and assumed to be homothetic, no inputs other than US and Canadian aluminum being considered, and the output prices of aluminum users have been normalized to one. Further it is assumed that US aluminum users' output prices are unaffected by changes in aluminum prices.

On the supply side, there are n_1 (n_2) symmetric US (Canadian) producers of aluminum, where the profit function of a typical US (Canadian) aluminum producer is:

$$\pi_1 = (p_1 - c_1) q_1 \tag{A7}$$

$$\pi_2 = (p_2 - c_2) q_2 , \tag{A8}$$

where q_i, p_i, and c_i are US and Canadian producer's output, selling price and costs respectively. If producers maximize profits with respect to output, the first-order conditions for representative US and Canadian producers are:

$$p_1 - c_1 + q_1\left[\frac{\delta p_1}{\delta Q_1}\frac{\delta Q_1}{\delta q_1} + \frac{\delta p_1}{\delta Q_2}\frac{\delta Q_2}{\delta q_1}\right] = 0 \tag{A9}$$

$$p_2 - c_2 + q_2\left[\frac{\delta p_2}{\delta Q_2}\frac{\delta Q_2}{\delta q_2} + \frac{\delta p_2}{\delta Q_1}\frac{\delta Q_1}{\delta q_2}\right] = 0\,, \tag{A10}$$

Aggregating over US (Canadian) producers, gives:

$$p_1 - c_1 - Q_1\lambda_1 = 0 \tag{A11}$$

$$p_2 - c_2 - Q_2\lambda_2 = 0\,, \tag{A12}$$

where λ_i are parameters measuring the gap between price and marginal cost in each sector.

In order to conduct comparative statics, and using the inverse demand functions (A3) and (A4), (A11) and (A12) can be re-written as:

$$(a_1 - c_1) - (b_1 + \lambda_1)Q_1 - kQ_2 = 0 \tag{A11'}$$

$$(a_2 - c_2) - (b_2 + \lambda_2)Q_2 - kQ_1 = 0\,. \tag{A12'}$$

Totally differentiating (11') and (12') gives:

$$\begin{bmatrix} (b_1+\lambda_1) & k \\ k & (b_2+\lambda_2) \end{bmatrix}\begin{bmatrix} dQ_1 \\ dQ_2 \end{bmatrix} = \begin{bmatrix} -dc_1 \\ -dc_2 \end{bmatrix}, \tag{A13}$$

which after re-arranging can be written as:

$$\begin{bmatrix} dQ_1 \\ dQ_2 \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} (b_2+\lambda_2) & -k \\ -k & (b_1+\lambda_1) \end{bmatrix}\begin{bmatrix} -dc_1 \\ -dc_2 \end{bmatrix}, \tag{A14}$$

where $\Delta = \{(b_1+\lambda_1)(b_2+\lambda_2) - k^2\}$.

In order to use the model for policy simulation, it is necessary to have estimates of the parameters in the demand system. This is done by taking some of the parameter estimates from external empirical sources. The remainder, are calculated by calibrating the theoretical model such that the parameters are consistent with equilibrium in the market in a given period. Focusing on equations (A1) and (A2), there are five unknown parameters, A_1, A_2, B_1, B_2, and K. Since actual prices and quantities give two relations between them, three further relations are required to solve the system.

Expressions for the price elasticity of demand and elasticity of substitution can be derived and then set equal to empirically observed values. In the case of the price elasticity of demand, since US- and Canadian-produced aluminum are being treated as imperfect substitutes, it is interpreted as the effect of an equi-proportionate rise in the price of the two products on total US aluminum expenditure *E*. Therefore, letting $p_1 = p_1^0 P$ and $p_2 = p_2^0 P$, where p_1^0 and p_2^0 are initial prices and *P* is the proportional change factor, the aggregate expenditure for aluminum in the US can be written as:

$$p_1^0 Q_1 + p_2^0 Q_2 . \tag{A15}$$

Given that in the calibration, p_1 and p_2 are the initial prices and substituting equations (A1) and (A2) into (A15), the aggregate expenditure index can be written as:

$$E = p_1 A_1 + p_2 A_2 - (B_1 p_1^2 + B_2 p_2^2 - 2Kp_1 p_2)P . \tag{A16}$$

The total market elasticity of US demand for aluminum, ε, is then defined and evaluated at the baseline point where the proportional change factor *P* equals 1. By differentiating (A16) with respect to *P* and multiplying by *P*/*E*, the elasticity of demand is given by:

$$\varepsilon = \frac{-\left(B_1 p_1^2 + B_2 p_2^2 - 2Kp_1 p_2\right)}{Q} . \tag{A17}$$

The elasticity of substitution would normally be defined as:

$$\sigma = d\log(Q_1 / Q_2) / d\log(p_1 / p_2) , \tag{A18}$$

which gives a fourth relation between the parameters when set equal to an external estimate of σ. However, equations (A1) and (A2) in general define the ration Q_1 / Q_2 to be a function of the vector (p_1, p_2) and not in terms of p_1 / p_2. In order for Q_1 / Q_2 to be a function of p_1 / p_2, at least locally, the parameters must satisfy the following final expression:

$$p_1(A_1 K + A_2 B_1) = p_2(A_2 K + A_1 B_2) . \tag{A19}$$

Given the definition of σ in (A18), and using equations (A1), (A2), and (A19), the final expression for the elasticity of substitution can be derived as:

$$\sigma = \frac{(p_1 / p_2)(B_1 B_2 - K_2)}{[B_1(p_1 / p_2) - K][B_2) - K(p_1 / p_2]} . \tag{A20}$$

Expressions (A17) and (A20) are then set equal to values of ε and σ reported in external empirical studies.

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Table 1: Market structure of North American aluminum industry

US Producer	Market Share (%)	Canadian Producer	Market Share (%)
Alcoa	50.8	Rio Tinto Alcan	51
Century Aluminum	21.2	Alcoa	31
Rio Tinto Alcan	5.3	Alouette	18
Columbia Falls Aluminum	5.0		
Other	17.7		

Source: USITC (2010); Natural Resources Canada (2009)

Table 2: Calibration data

p_1	2,660 ($/tonne)
p_2	2,794 ($/tonne)
Q_1	2,658,000 (tonnes)
Q_2	2,001,000 (tonnes)
Elasticity of demand	-0.54
Elasticity of substitution	3.5
c_1	1,800
c_2	1,800

Table 3: Calibrated parameters

Inverse demand functions		
a_1	7,585	
a_2	7,968	
b_1	0.00127	
b_2	0.00155	
k	0.00078	
Market power		
	Actual value	**Cournot-equivalent value**
λ_1	(10^{-4}) 3.23	(10^{-4}) 4.30
λ_2	(10^{-4}) 4.96	(10^{-4}) 6.00

Table 4: Welfare effects of US carbon pricing ($ billion)

Variable	(1) Pre-US policy	(2) US carbon pricing	(3) Volume BTA	(4) Share BTA
Producer profits	2.32	1.96	2.03	2.18
User surplus	11.77	11.15	10.92	10.40
Tax revenue	0.00	0.46	0.74	1.30
Social cost	0.52	0.49	0.49	0.50
Social welfare	13.58	13.08	13.20	13.40
Change in social cost	-	0.03	0.03	0.02
Deadweight loss	-	-0.17	-0.12	-0.06
Net deadweight loss	-	-0.14	-0.09	-0.04
Effective carbon price ($/t$CO_2$) (US, Québec)	-	282, 84	282, 84	282, 84
BTA ($/t)	-	-	141	469
Market share (%)	58	56	56	58
Emissions (CO_2t - millions)	24.70	23.31	23.41	23.64
Leakage	-	0.12	0.00	-0.78

Notes: Elasticity of demand = -0.54, elasticity of substitution = 3.5, and discount rate = 3%

Table 5: Sensitivity analysis of welfare effects of US carbon pricing ($ billion)

Variable	(1) Pre- US policy	(2) US carbon pricing	(3) Volume BTA	(4) Share BTA
Producer profits	2.32	2.05	2.09	2.18
User surplus	14.45	13.81	13.61	13.06
Tax revenue	0.00	0.47	0.70	1.30
Social cost	0.86	0.83	0.83	0.83
Social welfare	15.91	15.50	15.56	15.71
Change in social cost	-	0.03	0.03	0.02
Deadweight loss	-	-0.17	-0.15	-0.09
Net deadweight loss	-	-0.14	-0.11	-0.06
Effective carbon price ($/t$CO_2$) (US, Québec)	-	282, 84	282, 84	282, 84
BTA ($/t)	-	-	115	453
Market share (%)	58	56	56	58
Emissions (CO_2t - millions)	24.70	23.65	23.67	23.75
Leakage	-	0.10	0.00	-0.57

Notes: Elasticity of demand = -0.44, elasticity of substitution = 2.5, and discount rate = 2.5%