“Climate Policy and Border Measures:
The Case of the US Aluminum Industry”

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Abstract

In this paper, analysis is presented relating to the impact of border measures for climate policy on the problem of carbon leakage, and the related issue of competitiveness in the US aluminum industry, which can be characterized as oligopolistic. Specifically, it is shown that an appropriate border measure depends on the nature of competition in aluminum production, as well as the basis for assessing the trade neutrality of any border measure. If trade neutrality is defined in terms of market volume, even though carbon leakage is reduced, US aluminum producer competitiveness cannot be maintained. This compares to defining trade neutrality in terms of market share, which results in US aluminum producer competitiveness being maintained and global carbon emissions being reduced. In either case, US users of aluminum incur deadweight losses.

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 (Frankel, 2009). However, successive failures of the United Nations Climate Change Conference (UNCCC) in Copenhagen (2009), Durban (2011), and most recently Warsaw (2013), 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 (Bednar-Friedel, Schinko and Steininger, 2012).

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 are also currently applied in several countries, most notably Australia. In the case of the current European Emissions Trading Scheme (ETS), Canadian provinces such as Québec, and also 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.[1]

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

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[1] In the 111th US Congress, a climate bill sponsored by Representatives Waxman and Markey and passed by the US House of Representatives would have established a cap-and-trade system similar to that being operated in the EU.

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 (Frankel, 2009). 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 firms in industries most affected by domestic climate policies (WTO/UNEP, 2009; Böhringer, Balistreri, and Rutherford, 2012).

As Karp (2010) has recently pointed out, these two related concerns have their basis in the economics of *pollution havens*, which are defined as:

> "…a region or country with a concentration of pollution-intensive activity that has been induced by pollution policy that is weak relative to its trading partners…" (Copeland and Taylor, 2003, p.143)

Through its effect on relative prices, unilateral application of tougher climate policy by one country/region reduces the international competitiveness of energy-intensive industries in that country/region relative to another country/region that has weaker climate policy, the latter becoming a pollution haven (Burniaux, Martin and Oliviera-Martins, 1992; Pezzey, 1992).[2] The increased concentration of pollution-intensive activity in a country/region with weaker climate policy is the basis for the now widely used concept of carbon leakage, i.e., the increase in carbon emissions in locations where climate policy is weak as a proportion of the reduction in carbon emissions in locations that have stringent climate policy (Perroni and Rutherford, 1993).

Detailed analysis of how countries might cooperate over climate policy has been conducted by several authors, including, *inter alia*, Hoel (1992; 1994), Carraro and Siniscalo (1993), and

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[2] This idea is often expressed in terms of the 'pollution haven hypothesis', which is a rather strong theoretical result, for which there is rather weak empirical support (Copeland and Taylor, 2004). This follows from the fact that trade specialization will be affected by other determinants of comparative advantage. However, there is more empirical support for the related 'pollution haven effect' whereby implementation of tougher environmental policy in one country deters its exports (encourage its imports) of goods that embody a public bad(s) (Taylor, 2004).

Barrett (1994a). In the context of the current paper, there has also been a specific focus on 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 (Hoel, 1996; Mæstad, 1998). Hoel (1996), for example, 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.[3] Along similar lines, Gros and Egenhofer (2011) argue that the EU could influence global carbon emissions by imposing a tariff on the carbon content of all goods imported from countries that do not have a carbon-pricing mechanism in place, while Helm *et al*. (2012) show that use of import tariffs by a sub-set of countries that have implemented carbon pricing schemes will provide incentives to other countries to introduce their own schemes, thereby expanding the "coalition of the willing" (p. 392).

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 view of economists is that the principle for their use in the presence of a domestically imposed excise tax is well-founded in the literature on the impact of *origin* vs. *destination-based* taxation systems (Lockwood and Whalley, 2010). A synthesis of the analysis of this issue by Lockwood, de Meza and Myles (1994) shows that as long as a domestic tax is applied uniformly across all goods, and BTAs are set no higher than the domestic tax, if either prices or exchange rates are flexible, movement

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[3] A similar result was derived in an earlier paper by Markusen (1975).

between an origin and a destination base for taxation has no real effects on trade, production and consumption.

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 (WTO, 1997).

While there has been considerable discussion about the legal permissibility of BTAs for domestic climate policy, from the standpoint of this paper, two key aspects of the legal debate remain unresolved.[4] 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 steel production such as electricity, which is not physically present in the final good. Pauwelyn (2007) argues convincingly that if an 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 (2007) argues that if

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[4] For example, see *inter alia*, Pauwelyn (2007), Hufbauer, Charnovitz and Kim (2008), Horn and Mavroidis (2010), Tamiotti (2011), and Messerlin (2012).

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.[5]

Although the use of BTAs is not a particularly new regulatory issue, picking the appropriate level at which they are analyzed is important. A recent study by Mattoo and Subramanian (2012), which was reported widely in the media – e.g., The Economist (February 23, 2013) - contains analysis of the likely effects of BTAs based on domestic carbon content and applied to all merchandise imports as well as exports. This of course fits with the system of destination-based taxation discussed earlier. However this and other studies using computable general equilibrium (CGE) modeling may be based on inappropriate sector-level aggregation, especially when the objective is to establish the industry-specific effects of implementing climate policy in conjunction with BTAs (Böhringer *et al.*, 2012; Caron, 2012). As Karp (2010) shows, general equilibrium effects of climate policy may either moderate or reinforce the partial equilibrium effects, depending on how factor prices adjust – the latter being assumed away in a partial equilibrium setting. This suggests that in empirical work, both approaches matter: partial equilibrium models can identify an explicit relation between the magnitudes of the leakage and competitiveness effects and a few relevant parameters, and the effect of chosen parameter values on any estimates. As a consequence, partial equilibrium estimates are also a useful prelude to the

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[5] In the case of a domestic regulation on carbon emissions, Pauwelyn (2007) argues that imposition at the border of a similar regulation on imports of energy-intensive products is less likely to withstand WTO scrutiny.

construction of CGE models where the relation between modeling assumptions and model outcomes is not always very transparent.

While the issues of 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 firms, 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 firms (WTO/UNEP, 2009). In the case of perfectly competitive firms, atomistic firms make zero economic profits in long-run equilibrium. Consequently, if firms 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 firms 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,* Barrett (1994b), Conrad (1993), and Kennedy (1994). The key point of this previous literature is that if firms earn positive economic profits, implementation of climate policy and/or a BTA may have the effect of shifting profits between domestic and foreign firms, thereby affecting the former's competitiveness.

In the case of the US, Houser *et al*. (2009) identify five energy-intensive industries most likely to be affected by domestic climate policy: steel, aluminum, chemicals, paper and cement, where energy accounts for between 10 and 25 percent of total costs. A similar set of industries have been discussed with respect to EU concerns about carbon leakage (Monjon and Quirion, 2010). Several authors analyzing the carbon leakage/competitiveness issue have already modeled firm behavior in these industries as oligopolistic, e.g., steel (Smale *et al*., 2006;

Demailly and Quirion, 2008; Ritz, 2009)[6]; paper (Smale *et al*., 2006) and cement (Smale *et al*., 2006; Ponssard and Walker, 2008), and there is also empirical evidence that firms in these industries may behave less than competitively, e.g., steel (Gallett, 1996); aluminum (Yang, 2001; 2005); paper (Mei and Sun, 2008); and cement (Azzam and Rosenbaum, 2001).

Given this background, the specific focus of this paper is on evaluating the effects of climate policy on the US aluminum industry, paying attention to both indirect and direct carbon leakage, as well as competitiveness in aluminum production. In analyzing this problem, the current paper is organized as follows: in section 1, the key characteristics of the US aluminum industry are described, followed in section 2 by outline of a simple model of an aluminum production sector that is oligopolistic; climate policy and BTAs are discussed in detail in section 3, and then the oligopoly model is then calibrated and used in section 4 to simulate the effects of BTAs for domestic climate policy on the US aluminum industry; finally, a summary of the paper and some conclusions are presented.

In previewing the results, the paper makes two contributions. First, characterizing behavior in the US aluminum industry as oligopolistic captures the link between carbon leakage and competitiveness, and how that link is sensitive to the nature of competition between aluminum producers. Importantly, it is shown that 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 their 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

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[6] Babiker (2005) also uses a computable general equilibrium (CGE) setting to analyze carbon leakage for a wide range of sectors where oligopolistic behavior is assumed. Other studies of the energy-intensive industries do not account for imperfectly competitive behavior, e.g., Aldy and Pizer (2011) for the US, and Monjon and Quirion (2011) for the EU.

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). Specifically, the results show that the ability of a policymaker to prevent carbon leakage as well as maintain the competitiveness of import-competing firms is very sensitive to how one interprets the WTO/GATT rules on BTAs. In addition, absent a production subsidy targeted at US aluminum producers, users of aluminum incur deadweight losses from these policy choices as aggregate aluminum production is reduced by oligopolistic firms.

1. The US Aluminum Industry

The focus of this paper is on the US aluminum industry, with specific reference to the production of primary aluminum. 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 the most exposed to international competition of the US industries listed (Houser *et al.*, 2008). In describing the industry, we briefly discuss the following characteristics: the technology of production and market structure.

(i) Technology of production

Primary unwrought 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 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, 2011).

(ii) Market Structure

The most complete data we have for market structure of the US aluminum industry is for 2008. With respect to the US industry, 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).

Interestingly, Canada's share of US aluminum imports has increased substantially since 2004, so 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 large multinational producers, Alcoa and Rio Tinto Alcan, who between them account for 24% of the world's aluminum production (Carbon Trust, 2011). These producers operate in both the US and Canada, although Alcoa clearly has more market share in Canada than Rio Tinto Alcan does.

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, with one plant in British Columbia, where electricity is produced entirely from hydro-electric sources (Natural Resources Canada, 2009). 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).

2. A Model of the US Aluminum Industry

In order to analyze the US aluminum industry, an oligopoly model due to Dixit (1988) is applied. Essentially, this is a specific version of the model used by McCorriston and Sheldon (2005a; 2005b) and Sheldon and McCorriston (2012).[7] The key difference between these two approaches is that our earlier analysis was restricted to a setting of Cournot with a general demand function, while the analysis used here is a more flexible conjectural variations model with linear demand that can easily be calibrated to available data for the aluminum industry and used for policy simulation. Of course the conjectural variations approach is well-known to be an unsatisfactory way of modeling oligopoly, the standard objection being that they represent an attempt to impose dynamic interaction of producers on a single-period game (Tirole, 1989). However, in empirical analysis, they are useful as a reduced-form way to represent alternative

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[7] This model has typically been used in the applied strategic trade literature, most notably by Dixit (1987) to the US automobile industry, and later by McCorriston and Sheldon (1993) to the UK fertilizer industry.

theories of oligopolistic behavior (Ritz, 2009). The latter point is particularly relevant in light of Eaton and Grossman's (1985) result that policy outcomes in oligopoly models are highly-sensitive to the underlying game played by firms.

Based on the previous section, 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.[8] In addition, US- and Canadian-produced aluminum has the potential to be imperfectly substitutable in production. 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, $f'(Q_i) > 0$, and we can allow for $f'(Q_1) \neq f'(Q_2)$, 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.

(i) Structure of the demand system

The aggregate derived demand functions for aluminum are given as:

$$Q_1 = A_1 - B_1 p_1 + K p_2 \qquad (1)$$

$$Q_2 = A_2 - K p_1 + B_2 p_2 \qquad (2)$$

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:

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[8] Given the structure of the industry described in the previous section, while it is possible for multinational firms with plants in both the US and Canada to switch production between the two countries, this is not modeled explicitly.

$$p_1 = a_1 - b_1 Q_1 - kQ_2 \tag{3}$$

$$p_2 = a_2 - kQ_1 - b_2 Q_2 \tag{4}$$

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 firms that use aluminum in the US as an intermediate input:

$$\Gamma_1 = f(Q_1, Q_2) - p_1 Q_1 - p_2 Q_2 \tag{5}$$

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

$$f(Q_1, Q_2) = a_1 Q_1 + a_2 Q_2 - 0.5\left(b_1 Q_1^2 + b_2 Q_2^2 + 2kQ_1 Q_2\right) \tag{6}$$

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.

(ii) Producers' behavior

On the supply side, there are n_1 and n_2 US and Canadian producers of aluminum respectively whose reactions to one another are treated as a Nash-equilibrium with conjectural variations, the latter being derived from producers' profit functions. The profit function of a typical US aluminum producer is:

$$\pi_1 = (p_1 - c_1) q_1 \tag{7}$$

where q_1 is its output, p_1 and c_1 being its selling price and costs respectively.

Suppose conjectures are denoted as $v_{i,j}$, where *i*,*j*=1,2, and are interpreted as the amount by which each producer *i* believes each other producer *j* will respond to a variation in its output. Hence a US aluminum producer expects US aluminum output Q_1 to increase by $1 + (n_1 - 1)v_{11}$

when it increases its output by one unit and imports of Canadian aluminum Q_2 to increase by $n_2 v_{12}$. If profits π_1 are maximized with respect to q_1, the first-order condition is given as:

$$p_1 - c_1 + q_1 \left[\frac{\delta p_1}{\delta q_1} \{1 + (n_1 - 1) v_{11}\} + \frac{\delta p_1}{\delta q_2} n_2 v_{12} \right] = 0 \tag{8}$$

If a US producer plays Cournot, it believes that its rival producers will not change output in response to a change in q_1, hence $\delta p_1 / \delta q_1 = b_1$, the slope of the inverse demand function. If the market were perfectly competitive, a change in one producer's output would have no effect on the market price, hence $\delta p_1 / \delta q_1 = 0$.

Aggregating the first-order conditions over n_1 (and by assumption identical) producers, gives:

$$p_1 - c_1 - Q_1 V_1 = 0 \tag{9}$$

where V_1 is the aggregate conjectural variations parameter. For Cournot behavior, $V_1 = b_1 / n_1$, and as n_1 increases, the more competitive is the Cournot outcome, and for perfectly competitive behavior, $V_1 = 0$. A similar expression can be derived for Canadian aluminum producers:

$$p_2 - c_2 - Q_2 V_2 = 0 \tag{10}$$

With the relevant data, values for the conjectural variations parameters, V_1 and V_2 can be retrieved from (9) and (10).

In order to conduct comparative statics, and using the inverse demand functions (3) and (4), (9) and (10) can be re-written as:

$$(a_1 - c_1) - (b_1 + V_1) Q_1 - k Q_2 = 0 \tag{9'}$$

$$(a_2 - c_2) - (b_2 + V_2) Q_2 - k Q_1 = 0 \tag{10'}$$

Totally differentiating (9') and (10') gives:

$$\begin{bmatrix} (b_1+V_1) & k \\ k & (b_2+V_2) \end{bmatrix} \begin{bmatrix} dQ_1 \\ dQ_2 \end{bmatrix} = \begin{bmatrix} -dc_1 \\ -dc_2 \end{bmatrix} \tag{11}$$

which after re-arranging can be written as:

$$\begin{bmatrix} dQ_1 \\ dQ_2 \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} (b_2+V_2) & -k \\ -k & (b_1+V_1) \end{bmatrix} \begin{bmatrix} -dc_1 \\ -dc_2 \end{bmatrix} \tag{12}$$

where $\Delta = (b_1+V_1)(b_2+V_2) - k^2$.

3. Climate Policy and Border Tax Adjustments

(i) 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 greenhouse gas (GHG), 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 $g^e = t^e = m^e$. The imposition of g^e 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 the process of aluminum production being faced with a price of carbon. The cost increase to the domestic downstream firm also affects imports of Canadian aluminum, given by dQ_2 / dc_1. Following Ritz's (2009) technical specification of carbon leakage, which draws on the earlier definition of Perroni and Rutherford (1993), and assuming that US aluminum producers respond to g^e by reducing their intensity of carbon emissions via cleaner technology, carbon leakage l is given as:

$$l = \frac{de_2}{-de_1} \equiv \left[\frac{f'(Q_2)}{f'(Q_1)} . \frac{dQ_2}{-dQ_1} \right], \tag{13}$$

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, $dQ_2 / -dQ_1 > 0$. Equation (12) can be used to re-write (13) explicitly as:

$$l = \frac{de_2}{-de_1} \equiv \left[\frac{f'(Q_2)}{f'(Q_1)} . \frac{\Delta^{-1} k dc_1}{-\{\Delta^{-1}(b_2 + V_2) dc_1\}} \right] \tag{14}$$

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 $\Delta^{-1} k dc_1 > 0$ and $\{\Delta^{-1}(b_2 + V_2) dc_1\} < 0$, the direction of carbon leakage is given by $f'(Q_2)$ relative to $f'(Q_1)$ and the extent to which US (Canadian) aluminum producers cut (raise) output in response to US carbon pricing.

(ii) 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’, we consider the cases where the neutral BTA (*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 – what Bagwell and Staiger (2001a) have termed "regulatory chill". 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 not elicit a "non-violation" complaint to the WTO from Canada (Bagwell and Staiger, 2001b).

Import-volume neutrality

If neutrality is defined in terms of import volume, using (12), the appropriate BTA is given as:

$$\textit{neutral BTA} = \frac{(dQ_2 / dc_1)\ g^e}{-(dQ_2 / dc_2)} = \frac{\Delta^{-1}(k)g^e}{\Delta^{-1}(b_1 + V_1)} \tag{15}$$

When markets are perfectly competitive, $V_1 = 0$ and $k = b_1$, then $|dQ_2 / dc_2| = |dQ_2 / dc_1|$, the net effect of policies being such that $dQ_2 = 0$, i.e., the appropriate BTA should be set equal to the US carbon price of g^e. Specifically, with a carbon price of g^e, the BTA is effectively based on the carbon embodied in the domestically produced final good. This, rules out the domestic policymaker setting $t^b > g^e$ when $f'(Q_2) > f'(Q_1)$, i.e., given binding WTO/GATT rules, the appropriate BTA cannot be based on the carbon embodied in Canadian produced aluminum.[9]

In contrast, when markets are imperfectly competitive, $V_1 > 0$ and $k \le b_1$, setting the BTA equal to the price of carbon will lead to a non-neutral outcome - $dQ_2 \ne 0$, which also implies there will be carbon leakage. Using (12), $dQ_2 / dc_2 = \Delta^{-1}(b_1 + V_1) < 0$, i.e., the border tax reduces

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[9] Mattoo and Subramanian (2012) find significantly different trade effects of BTAs depending on whether they are based on the carbon content embodied in final goods produced in the importing country or the carbon content embodied in the imported goods.

the level of US aluminum imports, and $dQ_2 / dc_1 = \Delta^{-1} k > 0$, i.e., US carbon pricing increases the level of its aluminum imports. However, $\left| dQ_2 / dc_2 \right| > \left| dQ_2 / dc_1 \right|$, i.e., the absolute value of the own-effect of carbon pricing on Canadian producers is greater than the cross-effect of US carbon pricing on Canadian producers. Therefore, to ensure $dQ_2 = 0$, and also no carbon leakage, the BTA should be set less than the carbon price, $t^b < g^e$.

Import-share neutrality

In the case of import-share neutrality, the appropriate BTA is defined as one where the net effect of the carbon price g^e 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:

$$neutral\ BTA = \frac{[(dQ_2 / dc_1) + (dQ_1 / dc_1)]g^e}{[(dQ_1 / dc_2) + (dQ_2 / dc_2)]} = \frac{[\Delta^{-1} \{ k + (b_2 + V_2)\}]g^e}{[\Delta^{-1} \{ k + (b_1 + V_1)\}]} \qquad (16)$$

With perfect competition, where the parameters are such that, $V_i = 0$ and $k = b_1 = b_2$, then $[(dQ_2 / dc_1) + (dQ_1 / dc_1)] = [(dQ_1 / dc_2) + (dQ_2 / dc_2)]$, the net effect of policies being such that $d(Q_2 / (Q_1 + Q_2) = 0$, i.e., the appropriate BTA should again be set equal to the US carbon price of g^e. With imperfect competition, the magnitude of the BTA relative to the carbon price is dependent on the nature of competition between aluminum producers, as captured in V_i, 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 (16) is greater than the denominator, the BTA will be set above the domestic carbon price in order to satisfy neutrality, $t^b > g^e$. It is also possible under the latter circumstances that global carbon emissions may be reduced below that prior to implementation of domestic climate policy, i.e., there can be negative carbon leakage.

4. Model Calibration and Policy Simulation

(i) Calibration

Given the theoretical structure, and based on the methodology described in the Appendix, the demand system in equations (1) to (4) was calibrated for 2008, the year of most recent and complete data for the US and Canadian aluminium 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 aluminium 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 ε is based on a recent 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). Having calibrated the model, the parameter estimates shown in table 3 are consistent with equilibrium in the US aluminium industry in 2008.

Estimates of the conjectural variations parameters V_1 and V_2 derived from equations (9) and (10) are presented in table 4. For the purposes of comparison, the Cournot-equivalent values of V_1 and V_2 are also shown. The values indicate that, given the assumptions about North American producers' costs both US and Canadian producers were behaving more competitively than Cournot. However, interpreting the V_i directly is not easy, so here one can follow a procedure suggested by Dixit (1987): if the derived values of V_i actually reflected Cournot behaviour, then the Cournot-equivalent number of producers would be $n_i^c = b_i / V_i$; this can then be compared with the actual number of producers n_i, where n_i is based on the numbers-equivalent of the Herfindahl industry reported in section 1. The results of this comparison are reported in the lower of half of table 4, indicating that as $n_i < n_i^c$, both US and Canadian producers were behaving more competitively than Cournot in the US aluminum industry in 2008.

(ii) Policy Simulation

In deriving welfare effects of US carbon pricing and BTAs, it is necessary to write down the US social welfare function, W:

$$W = \pi_1 + \Gamma + g^e\{f'(Q_1)\}Q_1 + t^b Q_2 - d(e_1 + e_2) \qquad (17)$$

where the first and second terms refer to the profits of US aluminum producers and the surplus of US aluminum users respectively, the third term is the potential revenue raised from carbon pricing, the fourth term is 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). In considering (17), it should be noted that no attempt is made to either optimize W with respect to any of the variables on the right-hand side, or to evaluate the issue of where to target carbon emissions in a vertical production system.[10]

Welfare effects of US carbon pricing

Using the calibrated model, we first simulate the implementation in the US of a carbon price set at \$25/t CO_2, and borne by both US electricity producers and aluminum firms.[11] In order to calculate the impact of carbon pricing on US aluminum producers due to their indirect emissions via electricity generation, we first calculate the expected change in US electricity prices based on Fowlie's (2009) study of the California electricity industry. Based on assuming the electricity industry is characterized by Cournot behavior, she forecasts that carbon pricing would raise the

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[10] See Bushnell and Mansur (2011) for a discussion of vertical targeting and carbon leakage.

[11] This carbon price is based on Tol's (2005) mean CO_2 damage estimate.

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, based on accounting for both their direct and indirect carbon emissions.

Column (1) in table 5 reports the breakdown of social welfare pre-implementation of carbon pricing, 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 carbon pricing in column (2) of the table. The results indicate that the policy generates a 3.8% decline in social welfare, with the decline in profits and surplus of US aluminum producers and users respectively being partially offset by revenue raised from carbon pricing and 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, even though emissions decline by 5.7%.

The net deadweight loss of imposing a carbon price in the presence of imperfectly competitive behavior is also derived: the gross deadweight loss is calculated as the difference between the lost surplus of aluminum users due to producers raising aluminum prices, and the revenue raised from carbon pricing, and from this the reduction in the social cost of carbon emissions is deducted. The results indicate that there is net deadweight loss, which highlights a result discussed in detail by Conrad (1993): in the presence of oligopoly, 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 (oligopoly power). The implication is that in a second-best setting, the carbon price would likely have to be lower in order to minimize the net deadweight loss.

Welfare effects of US carbon pricing with BTAs

We then simulate the effect of implementation in the US of a carbon price in combination with a BTA on imports of Canadian aluminum. As before the carbon price is set at \$25/t CO_2, and is again borne by both US electricity producers and aluminum firms. The BTA is set according to whether neutrality is defined in terms of import- volume or import-share. In the case of a BTA designed to ensure that the volume of imports does not change after implementation of the carbon price, equation (15) indicates it should be set at \$138/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 (16) indicates it should be set at \$441/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 5.

In the case of the volume BTA, the results indicate that compared to setting a carbon price alone, the joint policy generates a lower decline in social welfare of 2.9% relative to the pre-policy benchmark. Again, the decline in profits and surplus of US aluminum producers and users respectively are partially offset by 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 unilateral implementation of a carbon price cannot be wholly resolved with a volume BTA. The results also indicate that there is a smaller net deadweight loss due to the fact that there are now two policy instruments available.

In the case of the share BTA, the results indicate that compared to setting a carbon price alone, the joint policy generates an even lower decline in social welfare of 1.3% relative to the pre-policy benchmark. Yet again, the decline in profits and surplus of US aluminum producers and users respectively are partially offset by 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 no longer lose market share, a function of Canadian producers maintaining their market share, and there is negative carbon leakage. The results also indicate that there is an even smaller net deadweight loss, again due to the fact that two policy instruments are being implemented. Note that the decline in the net deadweight loss is largely being driven by the increased tax revenue from the share BTA.

Welfare effects of US and Canadian carbon pricing with BTAs

The analysis outlined in the previous section assumes carbon pricing is not applied in Canada. However, 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 27,500 tons, 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 will receive 80-100% of their required emissions permits free of charge up to 2014, after which the number of free emissions permits they receive will decline 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).

Given this background, we simulate the effect of implementation in the US of both US and Canadian carbon prices in combination with a BTA on imports of Canadian aluminum. As before the US carbon price is set at \$25/t CO_2, borne by US electricity producers and aluminum firms, and the BTA is set according to whether neutrality is defined in terms of import- volume or import-share. The Québec carbon price is set at \$10.2/t CO_2, which is borne directly by Québec electricity producers, and passed on to Canadian aluminum firms, who as noted earlier, are almost exclusively located in Québec. Based on our earlier calculation of the effect of US carbon pricing on US aluminum production costs, we assume that Québec carbon pricing will translate 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 means that there is no additional direct increase in Canadian aluminum production costs: essentially, this acts as a partial alternative to a border tax rebate on Canadian aluminum exports. As noted earlier, under a destination-based taxation system, imports are taxed at the border, while exports receive a rebate at the border of any domestic tax.

The results of simulating the effects of US and Canadian carbon pricing are shown in table 6. Column (2) reports the breakdown of social welfare, 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 US carbon pricing only in column (2) of table 5. The results indicate that both countries applying carbon policy generates a slightly larger decline in social welfare of 4.4%, with the fall in profits and surplus of US aluminum producers and users respectively being partially offset again by revenue raised from carbon pricing and reduction in the social cost of emissions. In terms of competitiveness and carbon leakage, the results indicate US aluminum producers lose slightly less market share and there is positive carbon leakage, even though emissions decline by 5.5%. The results also indicate that there is a larger net deadweight loss from both US and Canadian carbon pricing, driven by the increase in aluminum prices in an oligopolistic setting. This emphasizes not only the earlier observation that in a second-best setting, the US carbon price would likely have to be lower in order to minimize the net deadweight loss, but also that Canadian exports of aluminum should receive a full border tax rebate of the Québec carbon tax.

The results of implementing either a volume or share BTAs are shown in columns (3) and (4) of table 6 respectively. In the case of the volume BTA, the results indicate that compared to setting US and Canadian carbon prices alone, the joint policy generates a lower decline in social welfare of 3.6% relative to the pre-policy benchmark shown in column (1) of table 6, although this is still a larger decline in social welfare compared to the case of US carbon pricing only. As before, the decline in profits and surplus of US aluminum producers and users respectively are partially offset by 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 now negative carbon leakage compared to the case of only US carbon pricing, i.e., the competitiveness problem of unilateral implementation of a carbon price still cannot be wholly resolved with a volume BTA. The results also indicate that there is a smaller net deadweight loss compared to the pre-policy benchmark due to the fact that there are now two policy instruments available.

In the case of the share BTA, the results indicate that compared to setting US and Canadian carbon prices alone, the joint policy generates an even lower decline in social welfare of 2.14% relative to the pre-policy benchmark. Yet again, the decline in profits and surplus of US aluminum producers and users respectively are partially offset by 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 again indicate that US aluminum producers no longer lose market share, a function of Canadian producers maintaining their market share, and there is negative carbon leakage. The results also indicate that there is an even smaller net deadweight loss with two policy instruments being implemented. Note that again, decline in the net deadweight loss is largely being driven by the increased tax revenue from the share BTA.

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 firms will become less competitive following unilateral implementation of domestic climate policy, but that there will be carbon leakage as market share shifts to foreign firms. 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 oligopoly is allowed for in US aluminum production, competitiveness can be defined in terms of rent-shifting between US and Canadian firms. Importantly, the extent of carbon leakage and reduction in competitiveness are both shown to be very dependent on how aluminum producers interact with each other in the presence of policies that affect their costs of production.

Assuming that the 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 the WTO/GATT rules on border tax adjustments are based on maintaining the volume of aluminum imports, there will be no carbon leakage, US firms incurring a reduction in output and lost profits and hence their competitiveness. In addition, this rule would rule out setting border tax adjustments targeted at the emissions level of Canadian aluminum producers. Alternatively, if the WTO/GATT rules on border tax adjustments are interpreted in terms of maintaining the 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 the WTO/GATT rules on border tax adjustments, users of aluminum actually suffer a net deadweight loss due to aggregate output of aluminum being reduced in an oligopolistic setting.

As noted in the introduction, a key issue in implementation of measures at the border for domestic climate policy is the extent to which an internal carbon price affects the costs of energy-intensive sectors. The main conclusion to draw from this paper is that failure to account for the extent to which climate policy is affected by the response of oligopolistic producers to changes in their costs has important implications for the implementation of WTO/GATT consistent border tax adjustments. Consequently, industrial organization does matter to the analysis of climate policy and border tax adjustments – something that other studies of this issue, such as Mattoo and Subramanian (2012), do not explicitly account for in their analysis.

Appendix: Model Calibration

In order to derive and assess the effects of a carbon tax and BTA, 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 (1) and (2), 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.

Following Dixit (1987), 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:

$$p_1^0 Q_1 + p_2^0 Q_2 \tag{A1}$$

Given that in the calibration, p_1 and p_2 are the initial prices and substituting equations (1) and (2) into (A1), the aggregate expenditure index can be written as:

$$E = p_1 A_1 + p_2 A_2 - (B_1 p_1^2 + B_2 p_2^2 - 2K p_1 p_2)P \tag{A2}$$

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 (A2) with respect to *P* and multiplying by *P*/*E*, the elasticity of demand is given by:

$$\varepsilon = \frac{-\left(B_1 p_1^2 + B_2 p_2^2 - 2K p_1 p_2\right)}{Q} \tag{A3}$$

Expression (A3) is then set equal to the observed value of ε.

The elasticity of substitution would normally be defined as:

$$\sigma = d\log(Q_1 / Q_2) / d\log(p_1 / p_2) \tag{A4}$$

which gives a fourth relation between the parameters when set equal to an external estimate of σ. However, as Dixit (1987) notes, equations (1) and (2) 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:

$$p_1(A_1K + A_2B_1) = p_2(A_2K + A_1B_2) \tag{A5}$$

Given the definition of σ in (A4), and using equations (1), (2), and (A5), the final expression for the elasticity of substitution can be derived as:

$$\sigma = \frac{(p_1 / p_2)(B_1B_2 - K_2)}{[B_1(p_1 / p_2) - K][B_2) - K(p_1 / p_2]} \tag{A6}$$

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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		

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)
ε	-0.54
σ	3.5
c_1	1,800
c_2	1,800

Table 3: Demand Parameters

Aggregate demand functions		Inverse demand functions	
A_1	4,093,320	a_1	7,585
A_2	3,081,540	a_2	7,968
B_1	1,135	b_1	0.00127
B_2	927	b_2	0.00155
K	567	k	0.00078

Table 4: Conjectural variations parameters

	Actual value	Cournot-equivalent value
V_1	(10^{-4}) 3.23	(10^{-4}) 4.30
V_2	(10^{-4}) 4.96	(10^{-4}) 6.00
	n_i	n_i^c
US	2.94	3.93
Canada	2.57	3.12

Table 5: Welfare Effects of US Carbon Policies (\$ billion)

Variable	(1) Pre-policy	(2) US carbon tax	(3) Volume BTA	(4) Share BTA
Producer profits	2.29	1.93	1.99	2.13
User surplus	11.72	11.09	10.87	10.39
Tax revenue	0.00	0.45	0.73	1.28
Social cost	0.52	0.49	0.49	0.49
Social welfare	13.49	12.98	13.10	13.31
Change in social cost	-	0.03	0.03	0.02
Deadweight loss	-	-0.17	-0.12	-0.05
Net deadweight loss	-	-0.14	-0.09	-0.03
Effective carbon price (\$/tCO$_2$) (US)	-	282	282	282
BTA (\$/t)	-	-	138	441
Market share (%)	57	54	55	58
Emissions (CO$_2$t - millions)	24.67	23.27	23.36	23.56
Leakage	-	0.13	0.00	-0.69

Table 6: Welfare Effects of US and Canadian Carbon Policies (\$ billion)

Variable	(1) Pre-policy	(2) US and Canadian carbon taxes	(3) Volume BTA	(4) Share BTA
Producer profits	2.29	1.97	2.03	2.17
User surplus	11.72	10.96	10.73	10.26
Tax revenue	0.00	0.46	0.73	1.26
Social cost	0.52	0.49	0.49	0.5
Social welfare	13.49	12.89	13.00	13.20
Change in social cost	-	0.03	0.03	0.02
Deadweight loss	-	-0.31	-0.26	-0.20
Net deadweight loss	-	-0.28	-0.23	-0.18
Effective carbon price (\$/tCO$_2$) (US, Québec)	-	282, 84	282, 84	282, 84
BTA (\$/t)	-	-	138	441
Market share (%)	57	55	56	59
Emissions (CO$_2$t - millions)	24.67	23.32	23.41	23.61
Leakage	-	0.06	-0.11	-1.22