Environmentally Damaging Electricity Trade*

Etienne Billette de Villemeur
Toulouse School of Economics (IDEI & GREMAQ)

Pierre-Olivier Pineau
HEC Montréal

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Abstract

Electricity trade across regions is often considered welfare enhancing. We show in this paper that this could be reconsidered if environmental externalities are taken into account. We consider two cases where trade is beneficial, before accounting for environmental damages: first, when two regions with the same technology display some demand heterogeneity; second when one region endowed with hydropower arbitrages with its "thermal" neighbor. Our results show that under reasonable demand and supply elasticities, trade comes with an additional environmental cost. This calls for integrating environmental externalities into market reforms when redesigning the electricity sector. Two North American applications illustrate our results: trade between Pennsylvania and New York, and trade between hydro-rich Quebec and New York.

Keywords: Electricity trade; Hydropower; greenhouse gas emissions.

1 Introduction

Electricity reforms across the world increasingly integrate various regions. In the United States, federal "open access" to transmission networks was mandated in 1996 through order 888 of the *Federal Energy Regulatory Commission*. In the European Union, the 2003 directive "EU common rules for the internal market in electricity" even go further by requiring all members to open their internal market and to offer choice to consumers. Integration reforms are also under way in Latin America and Africa. See for instance Pineau et al. (2004) and Pineau (2008). If little disagreement exists on the theoretical economic benefits of international trade (see for intance Bhagwati et al., 1998) and of electricity reforms, the environmental impacts of interregional electricity trade have not been studied in great details. A large literature exists on electricity

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market reforms (see for instance Stoft, 2002), but it largely ignores integration of different regions and environmental consequences.

DeCiccoa et al. (1992), however, raised some early concerns over new transmission lines in North America, and explore how efficiency improvements in consumption could avoid the need for these lines. Their focus is however not on emissions (mostly CO_2, NO_x and SO_x), which are usually considered the main environmental issues in the electricity sector. An important exception to this lack of attention on electricity, trade and the environment comes from the work of the *Commission for Environmental Cooperation of North America*. In 2002, they released a series of reports directly assessing possible environmental challenges and opportunities under a more integrated North American electricity market. See for instance CEC (2002). This work, however, revolves around energy models calibrated with given loads that have to be supplied (completely inelastic demand), and therefore offers limited validity in describing real electricity markets, where some demand elasticity exists, especially in the longer run. See also Bernard et al. (2004) for such a study of the impact on emissions of free-trade in the electricity sector in the North-American Northeast region (where important hydro and thermal capacity are available).

Furthermore, maybe because the project of mandating "Standard Electricity Market Design" in regional transmission organizations (RTOs) across the US was abandoned (FERC, 2005), the interest in environmental impacts of electricity trade decreased. Greenhouse gases (GHG) emissions related to the electricity sector remain however very important: about 25% of the worldwide GHG emissions come from the electricity sector (Baumert et al., 2005). There are many reasons to believe that a lot of environmental improvements could be achieved in electricity, notably through better resource allocation by the means of larger scale planning, capacity sharing and better electricity pricing (CEC, 2002). An example of poor resource allocation in this sector is, for instance, the case of hydropower in the US and Canada. In the US, most hydropower is sold at cost through federal non-profit power marketing administrations (like the *Bonneville Power Administration*), under the authority of the US Department of Energy. Similarly, in Canada, provinces such as British Columbia, Manitoba and Quebec, produce about 280 TWh of hydropower (Statistics Canada, 2008), sold at (low) historical cost within their own region. Neighboring provinces (Alberta, Saskatchewan, Ontario), because of their lack of access to hydropower, need thermal generation capacity and have electricity prices about twice higher (for price comparisons, see for instance Hydro-Quebec, 2008).

The benefits of trade between such "hydro" and "thermal" regions are obvious: hydropower plants can "shave" high production costs during peak hours while storing water during base periods, by buying cheaper thermal base load power. Crampes and Moreaux (2001) provide an economic model to study interactions between hydro and thermal units. Rangel (2008) reviews the market and regulatory issues that can arise in such situations, with a focus on possible market power abuses. He also reviews the literature of hydropower-dominated competition. Billette de Villemeur and Vinella (2008) extend Crampes and Moreaux (2001) to look at the optimal management when emissions from thermal units are accounted for.

This paper aims at providing some general results to better understand when electricity trade can be environmentally damaging, in the absence of any mechanism to account for environmental externalities, as it is currently the case for CO_2. In particular, we are interested in understanding and making more explicit the role of own price elasticity of demand and supply in electricity trade. Indeed, although elasticity plays a very important role in markets, notably to mitigate market power and price volatility, it has been the focus of very few studies. Among them are Lafferty et al. (2001) and IEA (2003), taking a regulator and public policy perspective. Another notable exception is Siddiqui (2003), which looks at the role of price elasticity in determining the market equilibrium in a competitive spot market for electricity with forward contracts. Interregional trade is however not the focus of these studies. Many empirical studies estimate elasticities, with a focus on short and long term own price elasticity of demand. However, both time-of-use (TOU) elasticities and regional elasticities are increasingly being studied. Dahl (1993) provides a wide survey of energy price elasticities (see also Wade, 2003). For a more recent survey of TOU elasticities, see Lijesen (2007). Regional price elasticities analysis for electricity demand can be found in Bernstein and Griffin (2005), for the United States, and NIEIR (2007), for Australian States. To our knowledge, however, price elasticity of supply has not been estimated in the literature.

In order to study the links between electricity trade, environmental impact and price elasticities, two very common cases are covered. First, the situation of two neighboring regions equipped with similar generation technologies, but facing different demand levels and different price elasticities. Second, the situation of a "hydro" region (with regulated price), neighboring a "thermal" region, selling electricity at marginal cost. Our results show that because the quantity sold is likely to grow when there is trade between regions, environmental impacts also grow.[1] These results hold under conditions on demand and supply price elasticities we establish, and that are commonly satisfied in electricity markets.

The next section presents in greater details the model and our results. Section 3 provides some numerical illustrations and discussion points.

2 Trade resulting from demand and technology heterogeneity

In the next subsections, we consider first a one-period situation with two regions, both competitive (pricing at marginal cost), but facing different demand levels. If environmental damages are not accounted for, trade, that emerges as a result of this demand heterogeneity, improves the electricity market outcomes. Then, in the following subsection, trade emergence (and benefits) come from

[1] We only focus on the electricity market, and therefore consider that there is no substitute to electricity. In reality, there are substitutes to electricity consumption (such as higher energy efficiency or alternative fuels), with other environmental consequences. It is however beyond the scope of this paper to study these secondary environmental impacts.

technological differences: one region is endowed with hydropower and regulates price in its internal market, while the other region has thermal generation and is competitive. During the two-period situation (with demand heterogeneity between periods), the hydro region can arbitrage in the thermal one.

We assume that environmentally damaging emissions only come from the thermal technology and are strictly increasing with production.

2.1 Same technology, different demand, one period

Assume that two regions share an identical technology (presumably thermal, with similar costs and emissions) and that both markets are competitive. Electricity is not storable but there is demand heterogeneity so that trade may allow the overall production cost to decrease. Without any loss of generality, we assume that in autarky (superscript A) price $\underline{p}^A$ is lower in region $\underline{T}$, compared to the other $\overline{T}$, because of its lower demand:

$$\underline{p}^A = C'\left(\underline{Q}^A\right) < \overline{p}^A = C'\left(\overline{Q}^A\right),$$

where $C(\cdot)$, the production cost function, is increasing and convex, as it can realistically be assumed in a thermal system. $\underline{Q}^A$ and $\overline{Q}^A$ are the quantities produced and consumed in both regions.

Allowing exchange between both regions results in

$$\underline{p} = C'\left(\underline{Q}^D + Q_X\right) = \overline{p} = C'\left(\overline{Q}^D - Q_X\right),$$

where Q_X is the quantity exchanged between regions and $\underline{Q}^D$ and $\overline{Q}^D$ are the quantities required to meet local demand in, respectively, regions $\underline{T}$ and $\overline{T}$ ($\underline{Q}^S$ and $\overline{Q}^S$ represent supply in $\underline{T}$ and $\overline{T}$). However, in order to be more realistic we limit trade to the transmission line capacity K, so that $Q_X = K$. We assume that this transmission capacity is not used strategically by its owners. The total rent associated to it is $R = \left(\overline{p} - \underline{p}\right) K$. We do not make any assumption on how this rent is distributed among buyers, sellers and transmission right owners.

This means that a price difference will continue to exist between the two regions:

$$\underline{p} = C'\left(\underline{Q}^D + K\right) < \overline{p} = C'\left(\overline{Q}^D - K\right).$$

Four basic but important results are now discussed. First, the welfare implications for the exporting region, producing $\underline{Q}^S = \left(\underline{Q}^D + K\right)$ and selling it at price $\underline{p}$. Second, the welfare implications for the importing region, producing $\overline{Q}^S = \left(\overline{Q}^D - K\right)$ and selling it at $\overline{p}$. Then, the combined welfare impacts, ignoring environmental consequences. Fourthly, the conditions under which such trade can actually have a negative impact on the environment.

Figure 1 illustrates the situation. Region $\underline{T}$ (right panel) produces $\underline{Q}^S$ and exports quantity K to $\overline{T}$ (left panel). This reduces price in $\overline{T}$, from $\overline{p}^A$ to $\overline{p}$, but increases price in $\underline{T}$ from $\underline{p}^A$ to $\underline{p}$. These price changes affect both consumers and producers, while a rent R is created from such trade and congestion.

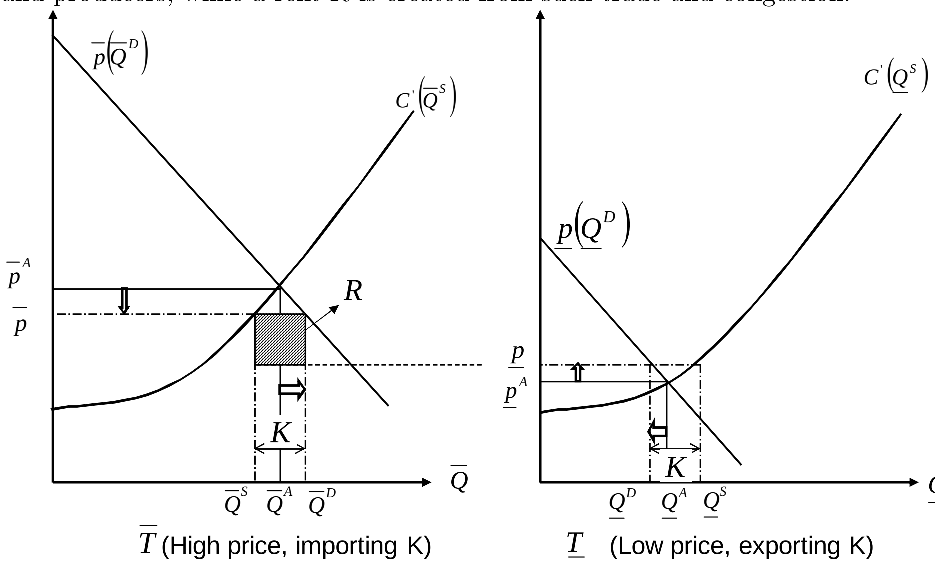

Figure 1. Trade under Demand Heterogeneity

2.1.1 Exporting region $\underline{T}$

Proposition 1 *It is always beneficial for a region facing a lower demand to export. If this region gets a share of the transmission rent, it is never optimal to allow trade up to price equalization. In the exporting region, trade redistribute wealth from consumers to producers.*
Proof. *See Appendix.* ■

This result is obvious, but it is useful to recall it for two reasons. First, the transmission constraint K between the two regions plays a key role in setting the profit level for the exporting region ($\underline{\pi}$). $\underline{T}$-producers require access to the market in $\overline{T}$, but not to the point of reaching an equal price level in both regions, if they own a share of the transmission rights. They may not directly control the level of K but will certainly lobby the transmission company in order to set a transmission capacity close to their interest.

Second, internally, consumers and producers in $\underline{T}$ have diverging interests: exports from $\underline{T}$ to $\overline{T}$ raise the price $\underline{p}^A$ to $\underline{p}$. Consumers will therefore apply some political pressure to prevent a connection to be established between the two regions. Overall, however, producers and consumers in $\underline{T}$ gain from trade, and in theory some transfer mechanisms could be designed to compensate $\underline{T}$-consumers from higher prices, in such a way that the two groups increase their position with trade, compared to autarky.

2.1.2 Importing region $\overline{T}$

Proposition 2 *Trade always improves upon welfare in the importing region; however, while consumers gain, producers lose.*
Proof. *See Appendix.* ■

In $\overline{T}$, as illustrated in Figure 1 and as it can also be obviously concluded, trade reduces price. This benefits consumers but hurts producers. This represents an incentive for producers to lobby against transmission lines making such trade possible, unless, of course, if they get a significant share of the transmission capacity rent. To some extent, it can explain why competitive regions such as Alberta (Canada) remain little interconnected with their neighbours, producing at lower costs. The empirical impact of such trade has been studied by Serletis and Dormaar (2007), and indeed imports into the Alberta market have been shown to reduce electricity price, which led Alberta producers to try to limit the impact of imports.

2.1.3 Combined regions

Proposition 3 *Neglecting environmental effects and transmission line construction costs, trade improves upon total welfare while prices are not equalized.*

This proposition simply results from combining welfare impacts in both regions (see also the appendix):

$$\frac{dW}{dK} = C'\left(\overline{Q}^D - K\right) - C'\left(\underline{Q}^D + K\right) = \overline{p} - \underline{p} \geq 0.$$

This result explains why trade is considered beneficial and promoted as good economic policy. However, marginal cost functions $C'(\cdot)$ are *private* cost functions that do not include the environmental costs of electricity production. As thermal electricity production from fossil fuels (coal, natural gas and oil) result in GHG emissions, among other gases, this welfare improvement for consumers and producers ignores the environmental costs of electricity production. If trade increases total electricity consumption (and therefore production), this reduces trade's benefits and may even make trade undesirable. We now turn our attention to this issue: when is trade actually increasing consumption and, consequently, the environmental impact?

2.1.4 Environmental Impact

Whether the overall consumption (and hence production) increases with trade depends on the price elasticity of demand in both regions ($\overline{\varepsilon}$ and $\underline{\varepsilon}$), on the price elasticity of supply ($\overline{\eta}$ and $\underline{\eta}$), on both demand levels and on the capacity of the transmission line.

Proposition 4 *Trade increases consumption when*

$$\frac{\overline{\varepsilon}}{\underline{\varepsilon}} > \frac{\overline{\eta}}{\underline{\eta}} \frac{\left(1 - K/\overline{Q}^D\right)}{\left(1 + K/\underline{Q}^D\right)}.$$

Proof. See Appendix. ■

This result provides a general condition that make precise when electricity trade increases total consumption, and therefore has a greater environmental impact (assuming environmental impact is increasing with production). It ties the ratio of demand elasticity to the ratio of supply elasticity, along with the transmission constraint (K) and demand levels ($\underline{Q}^D$ and $\overline{Q}^D$).

The (absolute value of the) demand price elasticity is often observed to be lower when demand is higher: $\overline{\varepsilon} < \underline{\varepsilon}$ (see some studies reviewed in Lijesen, 2007). Supply elasticity is lower when demand is higher (as capacity becomes more and more binding), so $\overline{\eta} \ll \underline{\eta}$. If these two inequalities hold, then the left hand-side of the condition would be greater than the right hand-side. Therefore, trade would lead to higher consumption levels and have a higher environmental impact. Illustrations of this result are presented in section 3.

2.2 Different technologies and regulations, two periods: the impact of hydro arbitraging

Our model of the electricity market with a hydropower region (H) follows Crampes and Moreaux (2001). The generation technology of the other region is thermal and is characterized by increasing and convex costs, as previously. Hydropower production is constrained by a known stock of water S. We assume that the hydropower system (reservoirs, dams and generating units) is calibrated such that this supply S exactly meets demand in this hydropower region. Yet, the stock S offers room for arbitrage, as water reserves can be freely allocated across time.

In order to illustrate the effects of this arbitrage, we shall analyze a very simple two-period model. More precisely, we assume that region H only produces hydropower while region T holds no hydro capacity (only thermal). Clearly, absent demand fluctuations in T price would be constant and there would be no place for trade, unless the H-producer is not compelled anymore to supply customers in its region. If, however, demand (and hence price) happens to vary in T, intertemporal arbitrage may help improve profitability and efficiency. We maintain our assumtion that transmission rights are not used strategically. To display clear cut results, we assume that they are either free or owned by the H-producer.

With regulated price in region H, neither price nor demand vary in that region. This says that the sum of the trade flows should add to exactly zero (no "loss of resource" for H-consumers). As a result, it must be the case that total production and consumption are equal in region T.

Let $\overline{p}_T^A$ and $\overline{Q}_T^A$ denote respectively the price and quantity in market T in the high (or peak) period, in autarky. The price $\underline{p}_T^A$ and the quantity $\underline{Q}_T^A$ denote the same values during the low (or base) period. By definition:

$$\overline{p}_T^A\left(\overline{Q}_T^A\right) = C_T'\left(\overline{Q}_T^A\right) > \underline{p}_T^A\left(\underline{Q}_T^A\right) = C_T'\left(\underline{Q}_T^A\right).$$

If there is an exchange of K between region H and T, then we have

$$\begin{aligned}\overline{p}_T\left(\overline{Q}_T^D\right) &= \overline{p}_T\left(\overline{Q}_T^S + K\right) = C_T'\left(\overline{Q}_T^S\right)\\ and\ \ \underline{p}_T\left(\underline{Q}_T^D\right) &= \underline{p}_T\left(\underline{Q}_T^S - K\right) = C_T'\left(\underline{Q}_T^S\right).\end{aligned}$$

Figure 2 illustrates the situation, which is very similar to the previous case (with trade between two thermal regions, $\underline{T}$ and $\overline{T}$). In Figure 2, however, only region T is illustrated, but each panel reflects a different period: the high demand period (left) and the low demand period (right). With trade constrained at K, price decrease from $\overline{p}_T^A$ to $\overline{p}_T$ during the high demand period, due to imports from H. Demand increases to $\overline{Q}_T^D$ due to the lower price. During the low demand period, price increases from $\underline{p}_T^A$ to $\underline{p}_T$, because H needs to get back the amount of energy K it previously sent to T. Demand decreases to $\underline{Q}_T^D$. This trade results in a profit π_H for the H-producer.

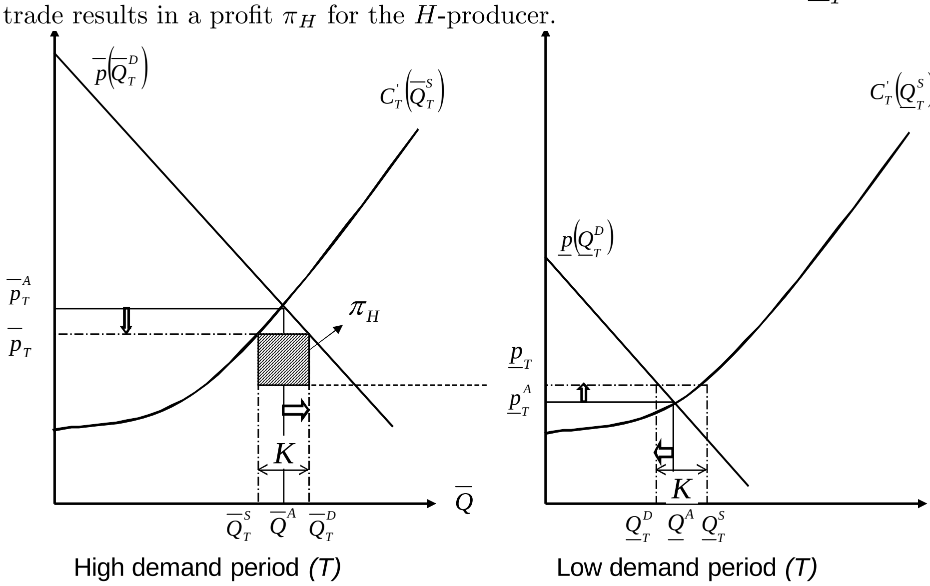

Figure 2. Trade under Technology Heterogeneity

In Figure 2, the increase in demand $\left|\overline{Q}_T^D - \overline{Q}^A\right|$ during the high demand period (left panel), appears to be larger than the decrease in demand $\left|\underline{Q}_T^D - \underline{Q}^A\right|$ during the low demand period (right panel). This would mean that overall, trade increases total consumption (and production), as consumption in region H remains equal due to the constant regulated price. Once again, our results show for the two regions the exact condition under which total consumption increases with trade.

2.2.1 Region H

Proposition 5 *It is always beneficial for a region with hydropower to arbitrage between high and low-demand periods within the thermal region. It is never*

optimal for the hydropower region to allow trade up to price equalization.
Proof. *See Appendix.* ■

When the hydropower region trades with the thermal one, it benefits from trade. However, in order to benefit from trade, the price differential between the two periods, $\left(\overline{p}_T - \underline{p}_T\right)$, has to remain strictly positive. This can only be achieved under a transmission constraint. The H-producer will therefore have an incentive to maintain it. H-consumers do not suffer from trade because price remain regulated in region H.

2.2.2 Region T

Proposition 6 *Trade improves upon welfare in the thermal region, however, T-consumers and T-producers can gain or lose depending on price and demand levels, transmission capacity and demand and supply price elasticities.*
Proof. *See Appendix.* ■

While trade is clearly beneficial in region T as a whole, there is no clear results on whether both consumers and producers gain, or only one of the two groups. Indeed, as shown in the appendix, under some conditions both group can gain from trade, but it could also be the case that one group is hurt by trade. Again, what occurs depends on the demand and supply price elasticities in both periods, as well as price, demand and transmission capacity levels.

2.2.3 Combined regions

Proposition 7 *Neglecting environmental effects and transmission line construction costs, trade improves upon total welfare while prices are not equalized.*
Proof. *See Appendix.* ■

Although trade clearly benefits both regions, the optimal situation where price are equalized in both time periods would destroy the trade benefits for the H-producer. There will therefore be some conflict between regions over which level of transmission should be build.

2.2.4 Environmental Impact

The environmental impact is exactly similar in this case as in the case previously studied. Total consumption will increase if

$$\frac{\overline{\varepsilon}}{\underline{\varepsilon}} > \frac{\overline{\eta}}{\underline{\eta}} \frac{\left(1 - K/\overline{Q}_T^D\right)}{\left(1 + K/\underline{Q}_T^D\right)}.$$

As production remains constant in H, the increased consumption has to be supplied from additional production in the thermal region, consequently releasing additional GHG.

3 Illustrations

To illustrate our results, we propose three cases. The first is a stylized example with a calibrated increasing and convex cost function, without empirical data. The second and third cases are based on the trade between two (mostly) "thermal" regions (New York and Pennsylvania) and between a "thermal" and a "hydro" region (New York and the province of Quebec, Canada). In all cases, we don't have to specify the demand side of the market, which maintains a level generality in our illustrations. We simply have to assume some own-price elasticity values for the demand of electricity. Elasticity of supply, in all cases, is derived from the generation cost function or observed price and supply data.

3.1 Stylized Example

For the sake of illustrating our results under a typical (and rather general) context, we use the following cost function for thermal generation:

$$C(Q^S) = c\left(Q^S + \exp\left(\frac{k_T}{K_T - Q^S}\right)\right).$$

Constants $c = 3.6103$, $K_T = 270$ and $k_T = 1251.6$ were calibrated to provide familiar values for marginal thermal production costs: $C'(0) = 10$ and $C'(100) = 250$ (in \$/MWh, for instance), with initial low-cost coal-generated electricity, then electricity generated from natural gas and finally from diesel power plants. The system has a theoretical maximum generation capacity of $K_T = 270$ (MW, for instance). However, the marginal production cost quickly becomes prohibitively high beyond 100 MW, as illustrated in Figure 3.

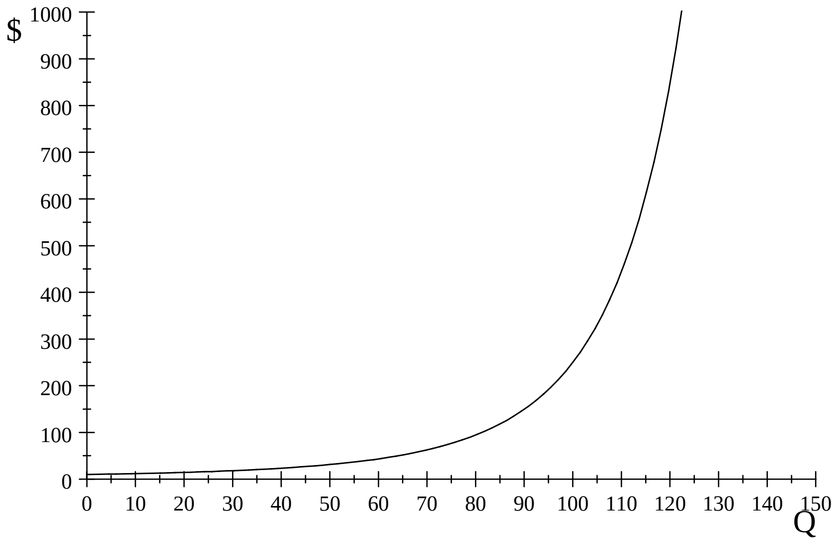

Figure 3. Marginal Production Cost

The corresponding supply elasticity $\eta(Q) = \frac{C'(Q)}{QC''(Q)}$ is illustrated in Figure 4. It tends to zero as production increases.

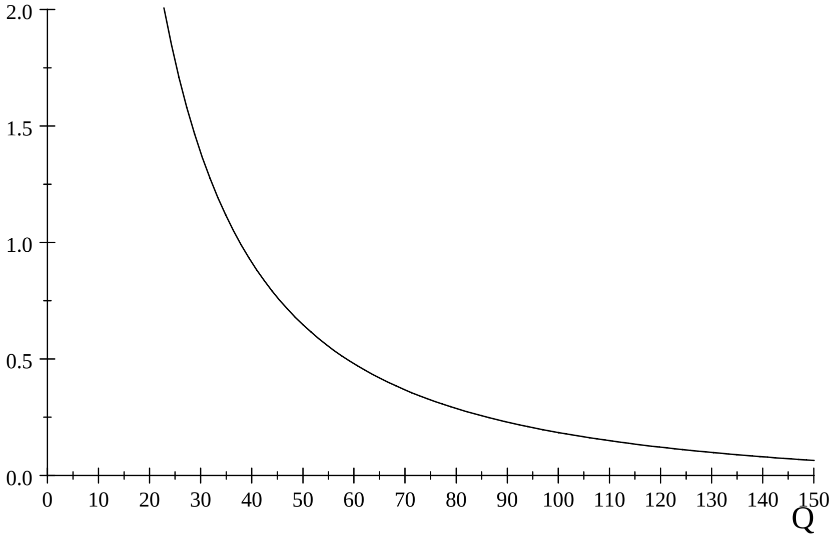

Figure 4. Supply Elasticity $\eta(Q) = \frac{C'(Q)}{QC''(Q)}$

The condition established in Proposition 4 is illustrated in Figure 5, where the Y-axis represents the ratio of peak to off-peak demand elasticity ($\overline{\varepsilon}/\underline{\varepsilon}$). The condition is respected above the bold line ($\left[\overline{\eta}\left(1 - K/\overline{Q}^D\right)\right] / \left[\underline{\eta}\left(1 + K/\underline{Q}^D\right)\right]$), which is always below $\overline{\varepsilon}/\underline{\varepsilon}$. The figure is drawn with $\underline{Q}^D = 40$ and a transmission capacity of 10. Demand in the "high demand" region $\overline{Q}^D$ is varying from 50 to 100 (X-axis in Figure 5), and the line $(\overline{\varepsilon}/\underline{\varepsilon}) = 1$ is also shown. What Figure 5 illustrates is how small the ratio of demand elasticities has to be in order to *not* have an increase in consumption with trade. If elasticities in both regions are similar, then $(\overline{\varepsilon}/\underline{\varepsilon}) \simeq 1$, trade will lead to more consumption and a greater environmental impact. If the ratio of demand elasticities is sufficiently small (below the bold line), then trade will decrease overall consumption. This would simply mean that first, the price reduction in the importing region (or during the high demand period, in the case of the hydro arbitraging) leads to little consumption increase, because it's relatively inelastic. Second, the price increase in the exporting region (or during the low demand period, in the case of the hydro arbitraging) leads to some important consumption reduction, because it's relatively elastic.

As consumption in $\overline{T}$ increases (shown in X-axis), the condition becomes more and more difficult to meet: demand elasticities in both region have to be extremely different (relatively a lot more inelastic in the importing region) in order to lower overall consumption.

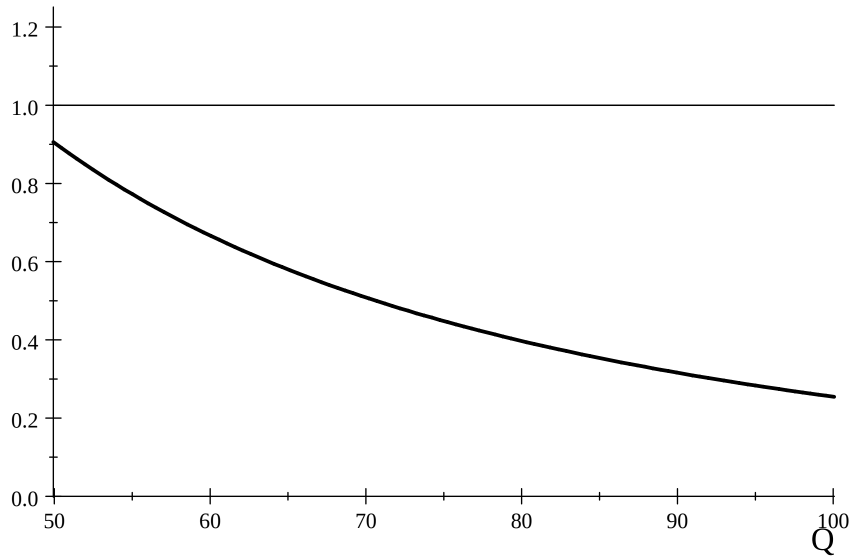

Figure 5. Proposition 4: $\frac{\overline{\eta}}{\underline{\eta}}\frac{\left(1-K/\overline{Q}^D\right)}{\left(1+K/\underline{Q}^D\right)}$ ($\underline{Q}^D = 40$; $K = 10$)

3.2 New York ($\overline{T}$) - Pennsylvania ($\underline{T}$) Illustration

The state of New York is interconnected with PJM (the region "Pennsylvania-New Jersey-Maryland") through transmission lines that have an import limit to New York of 3,160 MW (New York ISO, 2009a). For the sake of simplicity, we assume in this case that this interconnection is only with Pennsylvania (the largest state of PJM and the one with the longest border with New York). Both New York and Pennsylvania are dominated by thermal (fossil fuel) generation, with hydro and nuclear power representing less than 25% of their generation capacity in 2007 (EIA, 2009a).

Although the historical peak demand was higher in New York (33,939 MW; FERC, 2009a) than in Pennsylvania (31,618 MW; FERC,2009b, based on the 21.86% PJM load share of Pennsylvania; Monitoring Analytics, 2009a), Pennsylvania has a larger generation capacity (45,106 MW against 39,121 MW; EIA, 2009a). It also generated in 2008 a monthly average of 18.6 TWh against only 11.7 TWh for New York (EIA, 2009b), despite very similar monthly electricity sales within each state (12.6 TWh in Pennsylvania and 12.3 TWh in New York, all sectors combined; EIA, 2009a). The monthly average price in 2008, however, was about 40% cheaper in Pennsylvania than in New York (EIA, 2009c): 9.34¢/kWh against 16.38¢/kWh. It therefore makes a lot of economic sense for Pennsylvania to export to New York. However, these exports may or may not be environmentally beneficial overall if this type of trade increases consumption, especially since the marginal fuels in Pennsylvania are coal and natural gas (in 2008, respectively 78% and 17% of the time; Monitoring Analytics, 2009b).

Our result from proposition 4 allows to "test" if this trade is environmentally damageable or not, due to a higher overall electricity production, given that all parameters and variables can be approximated with confidence. Table 1 below summarizes these key elements.

	Value	Source
$\overline{Q}^D$	$33,939$	FERC (2009a)
$\underline{Q}^D$	$31,618$	FERC (2009b), Monitoring Analytics (2009a)
K	$3,160$	New York ISO (2009a)
$\overline{\varepsilon}$	-0.125	Bernstein and Griffin (2005, p.81)
$\underline{\varepsilon}$	-0.151	Bernstein and Griffin (2005, p.81)
$\overline{\eta}$	1.64	Own estimation from EIA (2009a and b)
$\underline{\eta}$	4.86	Own estimation from EIA (2009a and b)

Table 1. Key Parameters for the New York-Pennsylvania Illustration

Price elasticities of supply ($\overline{\eta}$ and $\underline{\eta}$) in Table 1 are estimated with monthly data, through a simple linear regression model. Although these values are very gross approximations, they reflect the fact that on a monthly basis, electricity generation in Pennsylvania is much more responsive to price than in New York, where the production capacity is much tighter, as monthly production and consumption numbers illustrate. Peak demand values are used simply to reflect an extreme situation. They make it more demanding for trade to induce more consumption; hence other values would only reinforce our conclusion.

With a demand elasticity ratio $\overline{\varepsilon}/\underline{\varepsilon} = 0.83$ greater than $[\overline{\eta}(1-K/\overline{Q}^D)]$ / $[\underline{\eta}(1+K/\underline{Q}^D)] = 0.28$, proposition 4 leads to the conclusion that overall electricity production (and consumption) increases with trade (exports) from Pennsylvania to New York. It would take an extremely inelastic demand in New York (-0.042 or more), or a much more elastic supply in this state (4.90 or more), to observe a decrease in overall consumption, and hence a lower environmental footprint.

3.3 New York (T) - Quebec (H) Illustration

New York, as previously mentioned, has a thermal generation system. If it can benefit from imports from another thermal system such as the one in Pennsylvania (due to demand heterogeneity), it can also benefit from the hydropower power system of the province of Quebec. This province regulates its electricity price to provide a constant price to its consumers, and has planned its hydropower system to meet its internal demand and to export. But if we abstract from the energy available for export in Quebec, there are still some trading opportunities for Quebec in New York, by simply arbitraging between high and low prices in the New York market. In this third case, we use New York City data (because this specific zone is highly congested), and the transmission capacity between New York and Quebec, to illustrate again the potential increase in environmental damage such trading can have.

Table 2 summarizes the value of key parameters and variables we need to illustrate this case.

	Value	Source
$\overline{Q}^D$	$7,017$	New York ISO (2009b)
$\underline{Q}^D$	$4,730$	New York ISO (2009b)
K	$2,125$	HQ TransEnergie (2009)
$\overline{\varepsilon}$	-0.125	Bernstein and Griffin (2005, p.81)
$\underline{\varepsilon}$	-0.151	Bernstein and Griffin (2005, p.81)
$\overline{\eta}$	0.17	New York ISO (2009b)
$\underline{\eta}$	0.20	New York ISO (2009b)

Table 2. Key Parameters for the New York-Quebec Illustration

$\overline{Q}^D$, the peak load demand, is the average of the 25% highest hourly loads in New York City, in January 2008 (values above the highest quartile of January 2008 hourly loads; New York ISO, 2009b). $\underline{Q}^D$, off-peak demand, is the average of the 25% lowest hourly loads. We use the value $K = 2,125$ MW because it is the export capacity from Quebec to New York. This represents a higher bound (any lower value could be used and would contribute to increase the right-hand side of the condition).

Estimates of price elasticity for demand during peak and off peak periods diverge in the literature. Surveys report different findings (Dahl, 1993; Lijesen, 2007), with many instance of higher elasticity values during peak load periods ($\overline{\varepsilon} > \underline{\varepsilon}$, in absolute values). When this happens, the inequality of proposition 4 can hardly be false, as illustrated in Figure 5. However, it is also plausible that during peak hours consumers have less options to react to prices, and hence we could observe $\overline{\varepsilon} < \underline{\varepsilon}$. Therefore, we keep the same values as before (but any other plausible values could be used).

Price elasticity values for supply are computed with January 2008 hourly prices (Location Based Marginal Price) and loads (Real Time Actual Load) for the New York City zone. Again, simple linear regression is used to compute the slope of the supply curve during the two different periods (peak and off-peak).

The demand elasticity ratio $\overline{\varepsilon}/\underline{\varepsilon} = 0.83$ is again greater than $[\overline{\eta}(1 - K/\overline{Q}^D)]$ / $[\underline{\eta}(1 + K/\underline{Q}^D)] = 0.41$. This means that arbitraging between peak and off-peak periods leads to an overall greater production in New York. In this case, it would take an extremely inelastic demand during the peak period (-0.061 or more), or a much more elastic supply during peak period (0.35 or more), to observe a decrease in overall consumption, and hence a lower environmental footprint. Alternatively, with all other values being equal, trade would lead to a lower overall consumption level only if K was under 79 MW.

3.4 Discussion

What these simple, but still realistic, illustrations show is that electricity trade, under very plausible conditions, lead to an increased overall consumption. Consequently, production is higher and the environmental impact grows. As GHG emissions become a worldwide concern and as electricity markets are increasingly being integrated, such results reinforce the argument that externalities have to be internalized in some ways into electricity prices, to avoid ignoring environmental impact when assessing trade gains.

The application of our main result over an extended period of time (with hourly loads), would allow a complete empirical assessment of the increased consumption induced by trade. The real environmental impact would have to account for the different emission levels along the supply curve as, for instance, coal-generated electricity is more CO_2 intensive than natural gas-generated electricity (about twice as intensive). This would mean that "cheap" production during off-peak hours are more environmentally damaging that "expensive" generation during peak hours. Consequently, the net environmental result of the higher consumption level could be even more difficult to assess, due to different externalities at different production levels. Indeed, to continue with the above example, if production during the low-demand period (or region) increases by δ, then production in the high-demand period (or region) would have to decrease by 2δ to obtain an "emission-neutral" net result. Under current market conditions, this would be very difficult to obtain.

4 Conclusion

This paper investigates issues seldom considered in the integration of electricity markets: welfare gains for both trade partners and welfare change for consumers and producers in each region. In addition, and this is its main results, it establishes that trade leads to higher consumption levels, and hence likely larger environmental impact, under very realistic conditions. The contribution of this paper is to center the analysis on price elasticities of both supply and demand. Three cases illustrates the main result. In each of them, environmental impact grows with trade.

Future work should focus on a thorough assessment of electricity trade between two regions and include actual emission levels of different fuels used in electricity generation.

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5 Appendix: Proof of Propostions 1 to 7

5.1 Proof of Proposition 1

Welfare impact in $\underline{T}$. *It is always beneficial for a region facing a lower demand to export. If this region gets a share of the transmission rent, it is never optimal to allow trade up to price equalization. In the exporting region, trade redistribute wealth from consumers to producers.*

Assume that trade is limited by transmission capacity K, so that $Q_X = K$. The effect of a small increase in K on the exporting region is obtained as follows. By differentiating the marginal pricing identity $\underline{p} = C'\left(\underline{Q}^D + K\right)$ with respect to K, one gets:

$$\frac{d\underline{p}}{dK} = \left[\left(\frac{d\underline{Q}^D}{d\underline{p}}\right)\frac{d\underline{p}}{dK} + 1\right] C''\left(\underline{Q}^D + K\right).$$

This rewrites directly as

$$\frac{d\underline{p}}{dK} = \frac{C''\left(\underline{Q}^D + K\right)}{1 + \left(\frac{-d\underline{Q}^D}{d\underline{p}}\right) C''\left(\underline{Q}^D + K\right)} \geq 0.$$

The marginal change in consumer (net) surplus $\underline{V}$ writes

$$\frac{d\underline{V}}{dK} = -\underline{Q}^D \frac{d\underline{p}}{dK},$$

which is negative.

Assume that the transmission rights owner makes a rent

$$R = \left(\overline{p} - \underline{p}\right) K.$$

The producers' profits $\underline{\pi}$ write $\underline{\pi} = \underline{p}\left(\underline{Q}^D + K\right) - C\left(\underline{Q}^D + K\right)$. Thus the marginal change in firms profits induced by trade is :

$$\begin{aligned} \frac{d\underline{\pi}}{dK} &= \frac{d\underline{p}}{dK}\left(\underline{Q}^D + K\right) + \left(\underline{p} - C'\left(\underline{Q}^D + K\right)\right)\left(1 + \frac{d\underline{Q}^D}{d\underline{p}}\frac{d\underline{p}}{dK}\right) \\ &= \frac{d\underline{p}}{dK}\left(\underline{Q}^D + K\right) \geq 0, \end{aligned}$$

as long as the capacity constraint is binding *i.e.* $\overline{p} > C'\left(\underline{Q}^D + K\right) = \underline{p}$.

Under the very same conditions, trade yields to a social welfare variation in the exporting region that writes

$$\frac{d\underline{W}}{dK} = \frac{d\underline{V}}{dK} + \frac{d\underline{\pi}}{dK} = \frac{d\underline{p}}{dK}K,$$

which is always positive.

In the exporting region, trade induces redistribution from consumers to producers. The net (marginal) impact of this redistribution is zero. The improvement in welfare comes from the marginal increase in profits made on the external market (as a result of the increase in price). Trade always improves upon autarky. The transmission rights owner makes a rent $R = \left(\overline{p} - \underline{p}\right) K$. It is never in its interest to increase the exporting capacity K up to a point where the price differential washes out.

5.2 Proof of Proposition 2

Welfare impact in $\overline{T}$. *Trade always improves upon welfare in the importing region; however, while consumers gain, producers lose.*

As previously, by differentiating of the marginal pricing equation $\overline{p} = C'\left(\overline{Q}^D - K\right)$, one gets the marginal effect of an increase in K upon the market price:

$$\frac{d\overline{p}}{dK} = \frac{-C''\left(\overline{Q}^D - K\right)}{1 + \left(\frac{-d\overline{Q}^D}{d\overline{p}}\right) C''\left(\overline{Q}^D - K\right)} \leq 0.$$

In the importing region, the change in capacity yields to a variation of consumer net surplus that writes

$$\frac{d\overline{V}}{dK} = -\overline{Q}^D \frac{d\overline{p}}{dK},$$

which is positive. The marginal impact on producers profits writes

$$\frac{d\overline{\pi}}{dK} = \frac{d\overline{p}}{dK}\left(\overline{Q}^D - K\right),$$

which is negative. However, the marginal impact on welfare is always positive:

$$\frac{d\overline{W}}{dK} = \frac{d\overline{V}}{dK} + \frac{d\overline{\pi}}{dK} = -K\frac{d\overline{p}}{dK}.$$

5.3 Total welfare and transmission rights owner

Combined welfare impact. *Neglecting environmental effects and transmission line construction costs, trade improves upon total welfare while prices are not equalized.*

Proposition 3 is proved in the process of studying the impact upon welfare of transmission capacity ownership.

If the rent made by the transmission right owner is given by $R = \left(\overline{p} - \underline{p}\right) K$, then effect of a marginal variation in K writes

$$\frac{dR}{dK} = \left(\overline{p} - \underline{p}\right) + K\left(\frac{d\overline{p}}{dK} - \frac{d\underline{p}}{dK}\right).$$

The variation in total welfare is given by

$$\begin{aligned}\frac{dW}{dK} &= \frac{d\underline{W}}{dK} + \frac{d\overline{W}}{dK} + \frac{dR}{dK} \\ &= \overline{p} - \underline{p}.\end{aligned}$$

The capacity K^* that maximizes welfare is such that $\overline{p} = \underline{p}$. The capacity that maximizes the rent R is defined by the implicit equation

$$K^R = \left(\frac{d\underline{p}}{dK} - \frac{d\overline{p}}{dK} \right)^{-1} \left(\overline{p} - \underline{p} \right).$$

Clearly $K^R < K^*$. If the transmission capacity is owned by the importing region, the capacity that maximizes the region welfare is defined implicitly by $(dR/dK) + \left(d\overline{W}/dK \right) = 0$, which yields $\overline{K}$

$$\overline{K}^* = \left(\frac{d\underline{p}}{dK} \right)^{-1} \left(\overline{p} - \underline{p} \right).$$

If the transmission capacity is owned by the exporting region, the capacity that maximizes the region welfare is defined implicitly by $(dR/dK) + (d\underline{W}/dK) = 0$, which yields $\underline{K}$

$$\underline{K}^* = \left(\frac{-d\overline{p}}{dK} \right)^{-1} \left(\overline{p} - \underline{p} \right).$$

Clearly both $\overline{K}^*$, $\underline{K}^*$ are higher than K^R and smaller than K^*.

5.4 Proof of Proposition 4

Environmental impact. *Trade increases consumption when*

$$\frac{\overline{\varepsilon}}{\underline{\varepsilon}} > \frac{\overline{\eta}}{\underline{\eta}} \frac{\left(1 - K/\overline{Q}^D\right)}{\left(1 + K/\underline{Q}^D\right)}.$$

The effect of a marginal increase in transmission capacity K upon aggregate demand Q^D writes

$$\frac{dQ^D}{dK} = \left(\frac{d\underline{Q}^D}{d\underline{p}} \right) \frac{d\underline{p}}{dK} + \left(\frac{d\overline{Q}^D}{d\overline{p}} \right) \frac{d\overline{p}}{dK},$$

where

$$\begin{aligned}\frac{d\underline{p}}{dK} &= \frac{C'' \left(\underline{Q}^D + K \right)}{1 + \left(\frac{-d\underline{Q}^D}{d\underline{p}} \right) C'' \left(\underline{Q}^D + K \right)}, \\ \frac{d\overline{p}}{dK} &= \frac{-C'' \left(\overline{Q}^D - K \right)}{1 + \left(\frac{-d\overline{Q}^D}{d\overline{p}} \right) C'' \left(\overline{Q}^D - K \right)}.\end{aligned}$$

This says that

$$\frac{dQ^D}{dK}=\frac{\left(\frac{-d\overline{Q}^D}{d\overline{p}}\right)C''\left(\overline{Q}^D-K\right)}{1+\left(\frac{-d\overline{Q}^D}{d\overline{p}}\right)C''\left(\overline{Q}^D-K\right)}-\frac{\left(\frac{-d\underline{Q}^D}{d\underline{p}}\right)C''\left(\underline{Q}^D+K\right)}{1+\left(\frac{-d\underline{Q}^D}{d\underline{p}}\right)C''\left(\underline{Q}^D+K\right)}.$$

Let $\underline{\varepsilon}$ and $\overline{\varepsilon}$ be the (absolute value of the) own-price demand elasticity in the exporting and importing region respectively:

$$\underline{\varepsilon}=\frac{\underline{p}}{\underline{Q}^D}\left(\frac{-d\underline{Q}^D}{d\underline{p}}\right)\quad \textit{and}\quad \overline{\varepsilon}=\frac{\overline{p}}{\overline{Q}^D}\left(\frac{-d\overline{Q}^D}{d\overline{p}}\right).$$

Similarly, let $\underline{\eta}$ and $\overline{\eta}$ be the supply elasticities in the exporting and importing region respectively:

$$\begin{aligned}\underline{\eta} &= \frac{C'\left(\underline{Q}^D+K\right)}{\left(\underline{Q}^D+K\right)C''\left(\underline{Q}^D+K\right)},\\ \overline{\eta} &= \frac{C'\left(\overline{Q}^D-K\right)}{\left(\overline{Q}^D-K\right)C''\left(\overline{Q}^D-K\right)}.\end{aligned}$$

The marginal change in total demand thus rewrites

$$\begin{aligned}\frac{dQ^D}{dK} &= \frac{\frac{\overline{Q}^D}{\overline{p}}\overline{\varepsilon}C''\left(\overline{Q}^D-K\right)}{1+\frac{\overline{Q}^D}{\overline{p}}\overline{\varepsilon}C''\left(\overline{Q}^D-K\right)}-\frac{\underline{\varepsilon}\frac{\underline{Q}^D}{\underline{p}}C''\left(\underline{Q}^D+K\right)}{1+\underline{\varepsilon}\frac{\underline{Q}^D}{\underline{p}}C''\left(\underline{Q}^D+K\right)}\\ &= \frac{\overline{\varepsilon}\overline{Q}^D}{\overline{\eta}\left(\overline{Q}^D-K\right)+\overline{\varepsilon}\overline{Q}^D}-\frac{\underline{\varepsilon}\underline{Q}^D}{\underline{\eta}\left(\underline{Q}^D+K\right)+\underline{\varepsilon}\underline{Q}^D}\\ &= \left[1+\frac{\overline{\eta}}{\overline{\varepsilon}}\left(1-\frac{K}{\overline{Q}^D}\right)\right]^{-1}-\left[1+\frac{\underline{\eta}}{\underline{\varepsilon}}\left(1+\frac{K}{\underline{Q}^D}\right)\right]^{-1}.\end{aligned}$$

Rearranging, this yields $\left(dQ^D/dK\right)>0$ if and only if

$$\frac{\overline{\varepsilon}}{\underline{\varepsilon}}>\frac{\overline{\eta}}{\underline{\eta}}\frac{\left(1-K/\overline{Q}^D\right)}{\left(1+K/\underline{Q}^D\right)}.$$

If emissions increase with total production, hence demand, we have there a necessary and sufficient condition for environmental damage to increase.

5.5 Proof of Proposition 5

Welfare impact in the H-region. *It is always beneficial for a region with hydropower to arbitrage between high and low-demand periods with a thermal* *region. It is never optimal for the hydropower region to allow trade up to price equalization.*

By assumption, region H is regulated. Absent over-capacity "prior to trade", the H-region is producing at capacity: $Q_H^D = Q_H^S = \max Q_H$. The average costs hence the price

$$p_H = C_H\left(Q_H^S\right)/Q_H^S$$

is given. It follows that trade has no impact upon consumers in the H-region.

Trade only impact firm H benefits. Service obligations impose the H-firm to clear demand in region H. Thus firm H must re-import any exported amount. We assume that exchanges are bounded by the transmission capacity so that $Q_X = K$. As a results profits write

$$\begin{aligned}\pi_H &= p_H Q_H^D - C_H\left(Q_H^S\right) + \left(\overline{p} - \underline{p}\right)K \\ &= \left(\overline{p} - \underline{p}\right)K,\end{aligned}$$

where $\overline{p}$ and $\underline{p}$ denote respectively the price in the T-region when the H-firm is exporting and importing, respectively. Observe that the pattern of trade does not bear any relationships with consumption in region H, provided the amount of trade (which is bounded by the trading capacity K) does not exceed the difference between H-supply and H-demand.

Clearly, from $\pi_H = \left(\overline{p} - \underline{p}\right)K$, it is always profitable for the H-firm (hence for the whole region) to arbitrage between high and low demand periods in the thermal region. However, since $\overline{p} \equiv \overline{p}\left(\overline{Q}_T^S + Q_X\right)$ is decreasing with $Q_X = K$ and $\underline{p} \equiv \underline{p}\left(\underline{Q}_T^S - Q_X\right)$ is increasing with $Q_X = K$, the H-region has an interest in limiting the capacity K.

5.6 Proof of Proposition 6

Welfare impact in T. *Trade improves upon welfare in the thermal region, however, T-consumers and T-producers can gain or lose depending on price and demand levels, transmission capacity and demand and supply price elasticities.*

Assuming again that trade is limited by the transmission capacity (that is $Q_X = K$), we know from previous calculus (proof of propositions 1 and 2) that the impact on prices over the different periods writes

$$\begin{aligned}\frac{d\underline{p}}{dK} &= \frac{C''\left(\underline{Q}_T^D + K\right)}{1 + \left(\frac{-d\underline{Q}_T^D}{d\underline{p}}\right)C''\left(\underline{Q}_T^D + K\right)}, \\ \frac{d\overline{p}}{dK} &= \frac{-C''\left(\overline{Q}_T^D - K\right)}{1 + \left(\frac{-d\overline{Q}_T^D}{d\overline{p}}\right)C''\left(\overline{Q}_T^D - K\right)}.\end{aligned}$$

It follows that

$$
\begin{aligned}
\frac{dV_T}{dK} &= -\overline{Q}_T^D \frac{d\overline{p}}{dK} - \underline{Q}_T^D \frac{d\underline{p}}{dK} \\
&= \frac{\overline{Q}_T^D C''\left(\overline{Q}_T^D - K\right)}{1 + \left(\frac{-d\overline{Q}_T^D}{d\overline{p}}\right) C''\left(\overline{Q}_T^D - K\right)} - \frac{\underline{Q}_T^D C''\left(\underline{Q}_T^D + K\right)}{1 + \left(\frac{-d\underline{Q}_T^D}{d\underline{p}}\right) C''\left(\underline{Q}_T^D + K\right)} \\
&= \frac{\overline{p}}{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}} - \frac{\underline{p}}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}}
\end{aligned}
$$

which is positive if and only if

$$
\frac{\overline{p}}{\underline{p}} > \frac{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}}.
$$

The marginal impact on industry profits writes

$$
\begin{aligned}
\frac{d\pi_T}{dK} &= \frac{d\overline{p}}{dK}\left(\overline{Q}_T^D - K\right) + \frac{d\underline{p}}{dK}\left(\underline{Q}_T^D + K\right) \\
&= \frac{\left(\underline{Q}_T^D + K\right) C''\left(\underline{Q}_T^D + K\right)}{1 + \left(\frac{-d\underline{Q}_T^D}{d\underline{p}}\right) C''\left(\underline{Q}_T^D + K\right)} - \frac{\left(\overline{Q}_T^D - K\right) C''\left(\overline{Q}_T^D - K\right)}{1 + \left(\frac{-d\overline{Q}_T^D}{d\overline{p}}\right) C''\left(\overline{Q}_T^D - K\right)} \\
&= \frac{\underline{p}\left(1 + \frac{K}{\underline{Q}_T^D}\right)}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}} - \frac{\overline{p}\left(1 - \frac{K}{\overline{Q}_T^D}\right)}{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}},
\end{aligned}
$$

which is positive if and only if

$$
\frac{\overline{p}}{\underline{p}} < \frac{\left(1 + \frac{K}{\underline{Q}_T^D}\right)}{\left(1 - \frac{K}{\overline{Q}_T^D}\right)} \frac{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}}
$$

Observe that trade may benefit both consumers and producers if

$$
\frac{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}} < \frac{\overline{p}}{\underline{p}} < \frac{\left(1 + \frac{K}{\underline{Q}_T^D}\right)}{\left(1 - \frac{K}{\overline{Q}_T^D}\right)} \frac{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}}.
$$

In all cases it is beneficial for the region T

$$\begin{aligned}\frac{dW_T}{dK} &= \left(\frac{d\underline{p}}{dK} - \frac{d\overline{p}}{dK}\right) K \\ &= \frac{\overline{p}\frac{K}{\overline{Q}_T^D}}{\left(1 - \frac{K}{\overline{Q}_T^D}\right)\overline{\eta} + \overline{\varepsilon}} + \frac{\underline{p}\frac{K}{\underline{Q}_T^D}}{\left(1 + \frac{K}{\underline{Q}_T^D}\right)\underline{\eta} + \underline{\varepsilon}} \geq 0,\end{aligned}$$

despite the rent R made by the Hydro-monopolist.

5.7 Proof of Proposition 7

Combined welfare impact. *Neglecting environmental effects and transmission line construction costs, trade improves upon total welfare while prices are not equalized.*

Clearly, it is profitable for region T to increase the transmission capacity K up to price equalization:

$$\frac{dW_T}{dK} = \left(\frac{d\underline{p}}{dK} - \frac{d\overline{p}}{dK}\right) K.$$

As already mentioned, region H would find profitable to limit this capacity to a level K^R such that

$$K^R = \left(\frac{d\underline{p}}{dK} - \frac{d\overline{p}}{dK}\right)^{-1} \left(\overline{p} - \underline{p}\right).$$

Yet, it is in the overall interest to constraint region H to export up to price equalization:

$$\frac{dW_T}{dK} + \frac{dW_H}{dK} = \left(\overline{p} - \underline{p}\right).$$