Electrified trade

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Abstract

The welfare effects of opening electricity markets to international competition depend on the capacity of the transmission line, the degree of competition in market for products using electricity as an input, and more remarkably on the distribution of firms between countries. In case of a small international electricity transmission capacity it is shown that both countries may gain or loose from the opening of electricity trade and the revenue of the system operator of the transmission grid may play a crucial role. The ambiguity carries over to the case of large transmission capacity but for different reasons.

The paper builds a two-tier a version of the Brander-Spencer -model to include vertical structure in the form of electricity production and competition between electricity producers. In the model the electricity producers behave strategically vis a vis each other even without transmission lines because electricity demand is derived demand. This aspect is ignored in the standard models of electricity markets.

PRELIMINARY, PLEASE DO NOT QUOTE

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1. Introduction

The paper makes a first attempt to study the implications of the international market unification taking into account explicitly the vertical relationship to electricity consumers and the ensuing welfare questions. The main point will bethat the welfare effects of electricity market unification are not clear. E.g. when electricity trade is opened but the transmission lines have a low capacity electricity

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price will increase in the countries where electricity initially was cheap and decline in the other countries. In the first set of countries the users of electricity will suffer while electricity producers will benefit. In the other countries exactly the opposite happens. It is shown that both countries can gain or loose simultaneously when electricity trade is opened. The profits of the system operator in charge of operating the international transmission grid may also be crucial for welfare to increase. When the transmission capacity is large the unified electricity price can be lower than the autarky prices helping inducing gains in both countries.

Electricity markets have faced a period of deep deregulation in many parts of the world. Notable examples are Nordic countries, UK and (parts of) USA. A remarkable component of deregulation has been the unification of markets. Mostly this has meant unification of national markets into a unified market but sometimes, like in Nordic countries, national markets have been unified into a truly international electricty market. EU accepted 2002 a plan to form EU wide electricity market.

With electricity markets several aspects due to the physical nature of the commodity traded must be considered. The first is that international trade in electricity requires transmission lines whose capacity is crucial for the strategic behavior of the firms. The transmission capacity constrains the net flows of electricity giving firms possibilities to congest or decongest the line. This leads to specific type of behavior at both ends of the line (Borenstein, Bushnell and Stoft 2000) and at the same end of the line (Willems 2002) and makes the organization of transmission rights important (Joskow and Tirole 2000). Since I am interested in the international electricity trade I focus on the first of these. The second aspect with electricity is that since electricity is an input to the production process[1] the vertical relationships between firms make it necessary to see electricity demand as derived demand more explicitly than is usually done. The welfare results depend crucially on the structure of the final goods market and on international differences in energy intensity of production. Explicitly deriving the derived demand for electricity reveals as a by product that in the standard work (see e.g. the references above) the increase in degree of competition due to opening of electricity trade may overestimated. If, as is usually done, the electricity suppliers are Stackelberg leaders then, assuming that energy users are competing with each other, then the electricity firms are competing with each other even before the transmission grid between the markets is built.

Otherwise electricity trade is just a special case of trade with inputs and final goods and raises similar issues as other studies on vertical supply relationships starting e.g. from Jones and Sanyal 1980 to economic geography (Fujita and Thisse 2001) and raising questions on firm strategies like vertical foreclosure (Jones and Spencer 1992) and foreign direct investment (Wong 1995). Also some aspects of the Dutch disease discussion are important but the discussion ignored the impacts of opening of international oil markets. However, research on taxation of oil imports and the role of monopolistic oil producers are relevant to some extent. Here I analyze a simple setting where electricity producers act strategically towards both final goods producers as well as against each other. Final good producers act strategically against each other but take electricity prices as given.

I shall modify the strategic trade model used by Brander and Spencer (1985) to incorporate electricity trade in a two-tier strategic trade model. It is a model suitable for the analysis of a small country case where final good producers sell most of their outputs to outside markets and are at the same time the major users of electricity. This is the case of e.g. paper and pulp and metal industries that are important in Nordic countries. It is the easiest model to highlight the importance and implications of the strategic interactions between firms in different layers of the "supply chain" and the intuition gained from the standard model can be utilized to understand the results.

The strategic relationships in the Brander-Spencer model imply that electricity price changes have effects beyond pure transfers beyween consumers and producers of electricity. An interesting aspect here is that within countries the interests of the electricity producers and producers using electricity differ. Due to international linkages though the interests are partially shared. It is exactly this that explains why the distribution of the firms in the final good market is crucial for the welfare effects. Both countries' welfare improves if the number of final good producers in the electricity exporting country is sufficient large relative to the number of final good producers in the country importing electricity when the transmission line has a small capacity. An interesting twist compared with the standard Brander-Spencer -model is that with small transmission capacity the electricity producer reacts passively to the electricity imports.

2. The Model

Assume that there are two countries, superscripted by H and F. Both of them are populated by two types of firms, firms producing final goods and firms producing electricity. The final good firms export their goods to third country markets and there exist n^j firms of this type in country j. These firms use both electricity and other inputs. There exists only one electricity producer/seller in each of the countries to highlight the international strategic implications of electricity transmission[2].

The inverse demand for the final good is given by

$$p = a - Q, a > 0 \tag{1}$$

where Q = aggregate sales and p = price of the good. The profits of a country j firm are

$$\pi^j = (a - Q_- - q)\, q - w^j \alpha^j q - r^j q \tag{2}$$

where q = output of the firm, Q_- = output by all the other firms, w^j = electricity price, α^j = electricity intensity of production and r^j = unit cost of inputs other than electricity. The final goods producers are engaged in Cournot competition with each other. From (2) the profit maximizing equilibrium output decisions when all firms in the same country are identical are:

$$q^j = \frac{a - \left(n^k + 1\right)\left(\alpha^j w^j + r^j\right) + n^k \left(\alpha^k w^k + r^k\right)}{N}, k \neq j \tag{3}$$

where $N \equiv n^H + n^F + 1$. The aggregate demand for electricity in country j is now $D^j = \alpha^j n^j q^j$. We follow the tradition in the electricity market analysis and assume that competition between electricity firms can be modelled as Cournot competition. Results from current research indicate that this assumption understates the degree of competition in electricity markets even though there is evidence from experiments that the degree of competition may come closer to Cournot competition as the players learn the rules of the game (Le Coq and Sturluson 2003).

In this sections it is assumed that there is now trade in electricity. Using (3) the inverse demand for electricity in j is

$$w^j = \frac{a - \frac{ND^j}{\alpha^j n^j} + n^k \left(\alpha^k w^k + r^k\right)}{\alpha^j \left(n^k + 1\right)} - \frac{r^j}{\alpha^j}, k \neq j. \tag{4}$$

This clearly still depends on the price of the electricity price in the other country and means that even without any transmission line the decisions of the electricity firms will be competing with each other. This fact is usually ignored in the models that start directly by assuming a demand function for electricity. Implicitly thus those models assume that the consumers of electricity are not competing in the same markets. (4) must be solved to get the final electricity inverse demand functions:

$$w^j = \frac{a}{\alpha^j} - \frac{D^j}{\widetilde{n}^j\left(\alpha^j\right)^2} - \frac{D^k}{\alpha^j\alpha^k} - \frac{r^j}{\alpha^j}, k \neq j \tag{5}$$

where $\widetilde{n}^j \equiv \frac{n^j}{n^j+1}$. I assume there to be one electricity firm in each country. With a larger number of firms the analysis becomes complicated as one must combine the strategic behavior of firms at the same end of the transmission line (as in Willems 2002) with strategic behavior of firms at opposite ends of the line (as in Borenstein, Bushnell and Stoft 2000). The profits of the electricity firm in j are:

$$\pi^{ej} = w^j D^j - c^j D^j \tag{6}$$

where $c^j =$ marginal cost of producing electricity. Using (5) and (6) the equilibrium Cournot electricity supplies are

$$D^j = \frac{M\widetilde{n}^j\alpha^j}{2}\left[\left(1-\frac{\widetilde{n}^k}{2}\right)a - \left(\alpha^j c^j - \frac{\widetilde{n}^k}{2}\alpha^k c^k\right) - \left(r^j - \frac{\widetilde{n}^k}{2}r^k\right)\right], k \neq j \tag{7}$$

where $M \equiv \frac{1}{1-\frac{\widetilde{n}^H\widetilde{n}^F}{4}}$. Denote these output levels by D^{jNT} (no electricity trade outputs). The main point to observe is that the structure of final goods markets has an impact on the decisions made by the electricity firms. The larger the number of firms in the home country of the electricity firm the larger will be the electricity supply. The larger the number of firms in the other country the stronger is the impact of changes in foreign costs on home electricity supply. Interestingly also the larger the number of foreign firms the smaller will be the impact of changes in aggregate demand for final goods (as measured by a) on home electricity supply. The resulting electricity prices are:

$$\alpha^j w^j = \left[1 - \frac{M}{2}\left(1 - \frac{\widetilde{n}^H \widetilde{n}^F}{2}\right)\right]\left(a + \alpha^j c^j - r^j\right) + \frac{M\widetilde{n}^k}{4}\left(\alpha^k c^k + r^k\right), k \neq j \quad (8)$$

where it is clear that $M\left(1 - \frac{\widetilde{n}^H \widetilde{n}^F}{2}\right) < 1$. The interesting point here is that increases in foreign costs of production (whether cost of final good or electricity production) will increase domestic price of electricity even without direct trade in electricity.

3. Electricity trade with small transmission capacity

Assume now that an electricity transmission grid with capacity K is installed. To have a genuine role for electricity trade it is assumed that without the transmission grid electricity price in H is lower than in F. I assume this differential to be due to the lower cost of producing electricity in H than in F. It is straightforward to calculate (from (8)) that a reduction in c^H and an increase in c^F increases the price differential if

$$\frac{\widetilde{n}^H}{2}\frac{\alpha^H}{\alpha^F} < 1, \frac{\widetilde{n}^F}{2}\frac{\alpha^F}{\alpha^H} < 1 \quad (9)$$

which are assumed to hold. The condition puts limits on the range of differences in energy intensity (noting that $\widetilde{n}^j \leq 1$) and/or number of firms to be considered.

If the transmission capacity is small then the one must specify how the capacity is allocated between producers. The usual assumption is that the grid is controlled by a system operator who has the task of allocating the transmission rights and charging the electricity suppliers for utilizing the grid. It is assumed that a system operator (**SO**) operates the grid aiming at efficient use of the grid. One way to achieve this is nodal pricing (see e.g. Borenstein, Bushnell and Stoft 2000). Nodal pricing implies that electricity prices are equated across markets if the capacity K is large enough so that the grid is not congested. If the capacity constraint binds then the operator rations capacity through prices. The producers obtain the price that prevails at the node at which they inject the electricity to the network while the consumers pay the price prevailing at the node where they are located. The system operator thus collects rents when the capacity is small. Electricity flows from the low price market to the high price market. It is natural to assume that the flow reduces the consumer electricity price differential. From (5) one gets for H price

$$w^H = \frac{a}{\alpha^H} - \frac{\left(D^H - K\right)}{\widetilde{n}^H \left(\alpha^H\right)^2} - \frac{\left(D^F + K\right)}{\alpha^H \alpha^F} - \frac{r^H}{\alpha^H} \tag{10}$$

and likewise for F:

$$w^F = \frac{a}{\alpha^F} - \frac{\left(D^F + K\right)}{\widetilde{n}^F \left(\alpha^F\right)^2} - \frac{\left(D^H - K\right)}{\alpha^H \alpha^F} - \frac{r^F}{\alpha^F} \tag{11}$$

The price differential clearly diminishes for given levels of electricity supply as capacity expands if

$$\widetilde{n}^H < \frac{\alpha^F}{\alpha^H}, \widetilde{n}^F < \frac{\alpha^H}{\alpha^F} \tag{12}$$

Clearly, if (12) holds then also (9) is automatically satisfied. We assume that (12) holds. I also assume that $\frac{1}{2} < \min\left\{\frac{\alpha^F}{\alpha^H}, \frac{\alpha^H}{\alpha^F}\right\}$ to make final good production possible in both countries.

Borenstein, Bushnell and Stoft (2000) have completely characterized the possible equilibria in this game between the electricity suppliers. Their results can be generalized with the assumptions made to the present context and are collected in the following lemma:

Lemma 1 *A pure-strategy equilibrium as the capacity K approaches 0 exists if and only if the electricity prices differ when no transmission grid exists. In this equilibrium electricity flow from the low price producer congests the transmission line. If K is large enough an unconstrained Cournot equilibrium exists. With intermediate capacities either no pure-strategy equilibria exist or there is an interval of capacities where both the unconstrained and grid congestion equilibria co-exist.*

In this paper only the congestion and unconstrained equilibria are studied. This section concentrates on the congestion equilibrium. It exists by Lemma 1 surely if the transmission capacity approaches 0 and electricity prices without trade differ between producers. If the final good market is large (a is large) then the pre-trade equilibrium electricity price in H is lower than in F if final good production is more energy intensive there than in F, i.e. if

$$\alpha^F < \alpha^H \tag{13}$$

which we assume to hold. Also, the lower the marginal cost of electricity production in H relative to F is the lower will the H electricity price be relative to F.

With nodal pricing the profits of the electricity producers are

$$\begin{aligned}\pi^{eH} &= \left[\frac{a}{\alpha^H} - \frac{\left(D^H - K\right)}{\widetilde{n}^H \left(\alpha^H\right)^2} - \frac{\left(D^F + K\right)}{\alpha^H \alpha^F} - \frac{r^H}{\alpha^H}\right] D^H - c^H D^H \\ \pi^{eF} &= \left[\frac{a}{\alpha^F} - \frac{\left(D^F + K\right)}{\widetilde{n}^F \left(\alpha^F\right)^2} - \frac{\left(D^H - K\right)}{\alpha^H \alpha^F} - \frac{r^F}{\alpha^F}\right] D^F - c^F D^F\end{aligned} \tag{14}$$

The profit maximizing equilibrium output levels are now

$$\begin{aligned} D^H &= D^{HNT} + \frac{M\widetilde{n}^H\alpha^H}{2}\left(T^H + \frac{\widetilde{n}^F}{2}T^F\right)K \\ D^F &= D^{FNT} - \frac{M\widetilde{n}^F\alpha^F}{2}\left(T^F + \frac{\widetilde{n}^H}{2}T^H\right)K \end{aligned} \tag{15}$$

where $T^H \equiv \frac{1}{\widetilde{n}^H\alpha^H} - \frac{1}{\alpha^F}$, $T^F \equiv \frac{1}{\widetilde{n}^F\alpha^F} - \frac{1}{\alpha^H} > 0$ by (12). In equilibrium the low price producer, H, behaves aggressively by expanding its output as the transmission line opens while the high cost producer reduces its supply (i.e. adjusts passively to the flow of electricity from the other country). The equilibrium electricity prices are

$$\begin{aligned} \alpha^H w^H &= \left(\alpha^H w^H\right)^{NT} + \left\{\left[1 - \frac{M}{2}\left(1 - \frac{\widetilde{n}^H\widetilde{n}^F}{2}\right)\right]T^H + \frac{M\widetilde{n}^F}{4}T^F\right\}K \\ \alpha^F w^F &= \left(\alpha^F w^F\right)^{NT} - \left\{\left[1 - \frac{M}{2}\left(1 - \frac{\widetilde{n}^H\widetilde{n}^F}{2}\right)\right]T^F + \frac{M\widetilde{n}^H}{4}T^H\right\}K \end{aligned} \tag{16}$$

where $\left(\alpha^j w^j\right)^{NT}$ is the electricity price when no trade in electricity is allowed (from (8)).

Using (16) the welfare impacts of electricity trade arise here from three sources: The impacts on profits of final good producers, the impacts on profits of electricity producers and impacts on profits of the system operator. The profits of the final good producers are (by using the first order condition associated with (2)) $n^j\left(q^j\right)^2$, and the profits of the electricity producer are $\frac{\left(D^j\right)^2}{\widetilde{n}\left(\alpha^j\right)^2}$. The revenue of the system operator is $\left(w^F - w^H\right)K$, the transmission rent multiplied by the amount of electricity transmitted. Let $c^o\left(K\right)$ denote the system operator's cost of running the trade and θ^j country j's share in system operator's profits. The aggregate welfare in country j is then

$$U^j = n^j \left(q^j\right)^2 + \frac{\left(D^j\right)^2}{\widetilde{n}^j \left(\alpha^j\right)^2} + \theta^j \left[\left(w^F - w^H\right) K - c^o\left(K\right)\right] \tag{17}$$

From (17) the change in welfare as the transmission capacity is increased is given by

$$2n^j q^j \frac{\partial q^j}{\partial K} + 2\frac{D^j}{\widetilde{n}^j \left(\alpha^j\right)^2}\frac{\partial D^j}{\partial K} + \theta^H \left[\left(w^F - w^H\right) - \left(c^o\right)'\left(K\right) + \frac{\partial\left(w^F - w^H\right)}{\partial K}\right] \tag{18}$$

Consider first the impacts on country H welfare. Since H is exporting electricity $\alpha^H n^H q^H = D^H - K$. Using (18) the welfare impact on country H has at $K = 0$ the same sign as the following expression:

$$\frac{\partial q^H}{\partial K} + \frac{1}{\widetilde{n}^H \alpha^H}\frac{\partial D^H}{\partial K} + \frac{\theta^H \left[\left(w^F - w^H\right) - \left(c^o\right)'\left(0\right)\right]}{\frac{2D^H}{\alpha^H}} \tag{19}$$

The first term in (19) is surely negative as the electricity trade increases the electricity price in H increasing the marginal cost of final goods producers. The second term is surely positive indicating that H electtricity supplier gets higher profits as the foreign market opens. The third term is non-negative as long as the marginal revenue from expanding capacity exceeds the marginal cost of running the electricity market when the transmission line is opened. I assume this to hold.

The first two terms in (19) can be collected to yield (using (3), (10), and (15))

$$\begin{aligned} \frac{\partial q^H}{\partial K} + \frac{1}{\widetilde{n}^H \alpha^H}\frac{\partial D^H}{\partial K} = \frac{M}{2}\left\{-\frac{n^F+1}{N} - \frac{n^H n^F}{2\left(n^H+1\right)N} + 1\right\}T^H + \\ \frac{M}{2}\left\{-\frac{n^F}{2N} - \frac{n^F}{N} + \frac{n^F}{2\left(n^F+1\right)}\right\}T^F \end{aligned} \tag{20}$$

where I have used the relation $1 - \frac{M}{2}\left(1 - \frac{\widetilde{n}^H \widetilde{n}^F}{2}\right) = \frac{M}{2}$.

Consider first the general case of any number of firms in both countries. Given (12) and (13) it is clear that the number of firms in H cannot be arbitrarily large while in F it can. It is easy to calculate (from (20)) that

$$\begin{aligned} &\frac{\partial q^H}{\partial K} + \frac{1}{\widetilde{n}^H \alpha^H} \frac{\partial D^H}{\partial K} = \\ &\frac{Mn^H}{2N\left(n^H+1\right)} \left[2\left(n^H+1\right) - n^F\right] T^H + \frac{Mn^F}{4}\left(-\frac{3}{N} + \frac{1}{n^F+1}\right) T^F \end{aligned} \tag{21}$$

(21) reveals that aggregate profits in electricity exporting country increase for sure if the number of final good producers in the exporting country is large enough and decrease if the number of final good producers in the electricity importing country is large enough. Because the country also shares in the **SO** profits we get

Proposition 2 *The country exporting electricity gains from opening of trade with small transmission capacity if a)* $n^H > 2\left(n^F+1\right)$ *and b) international differences in in energy intensities are small enough so that* $\frac{n^H}{n^H+1} < \frac{\alpha^F}{\alpha^H}$*. Aggregate profits in the exporting country decrease when electricity trade is opened if* $n^H < \frac{n^F}{2} - 1$*. In this case it is possible for the welfare to decline in the exporting country.*

The limits imposed by conditions a) and b) in the proposition are quite tight for the welfare gains to be sure. It is easiest to satisfy them when there exists only one final good producer in F but even then the condition b) requires that $\frac{\alpha^F}{\alpha^H} > \frac{4}{5}$. On the other hand, the country may loose whenever the number of foreign final good producers is large enough. The intuition for the result is that with sufficiently large number of home final good producers the adverse impacts of higher electricity price on their profits are mitigated while the competition from domestic producers checks the ability of foreign producers to gain from lower electricity price. The increase in electricity price in the exporting country is a kind of tax (familiar from the Brander-Spencer -model) on its final good producers which leads to shifting of rents to producers from the country importing electricity. The producers in the electricity importing country also receive an equivalent to export subsidy in the form of reduced electricity prices increasing further the rent shifting. The rent shifting is the more limited the larger the number of firms. The adverse impact on the exporter are smaller the larger the number of firms located there as they receive larger share of the profit.

To complete the picture we finally consider the case of the importing country. It is straightforward to calculate from (24) that

$$\begin{aligned} \frac{\partial q^F}{\partial K} + \frac{1}{\widetilde{n}F\alpha^F}\frac{\partial D^F}{\partial K} = \\ \frac{Mn^H}{4}\left(\frac{3}{N} - \frac{1}{n^H+1}\right)T^H + \frac{Mn^F}{4N\left(n^F+1\right)}\left[n^H - \left(2n^F+1\right)\right]T^F \end{aligned} \tag{22}$$

We have thus

Proposition 3 *The country importing electricity will gain from opening of electricity trade with small transmission capacity if a)* $n^H > 2\left(n^F+1\right)$ *and b) international differences in in energy intensities are small enough so that* $\frac{n^H}{n^H+1} < \frac{\alpha^F}{\alpha^H}$*. Aggregate profits in the importing country decrease when electricity trade is opened if* $n^H < \frac{n^F}{2} - 1$*. In this case it is possible for the welfare to decline in the importing country.*

The structure of final good market ensuring welfare benefits are the same for the electricity importing country as for the exporting country. The intuition here is that fewer final good producers in the importing country maximize the rent shifting to them while not preventing exporting country electricity producer increasing its profits enough by restricting the losses and reduction of electricity demand by exporting country final good producers.

The two last Propositions clearly imply that both countries can benefit from the opening of the electricity trade. The next proposition just records that:

Proposition 4 *Welfare in both countries opening mutual electricity trade (subject to small transmission capacity) improves, if a)* $n^H > 2\left(n^F + 1\right)$ *and b) international differences in in energy intensities are small enough so that* $\frac{n^H}{n^H+1} < \frac{\alpha^F}{\alpha^H}$.

But as is obvious from the both proposition, welfare can decline also:

Proposition 5 *Aggregate profits will decline in both countries opening mutual electricity trade (subject to small transmission capacity) if* $n^H < \frac{n^F}{2} - 1$*. Their welfare will decline if the marginal profits from the SO are small enough at low transmission capacity levels (e.g. due to large marginal costs). If the international differences in the energy intensity of final good production are large then the welfare impacts of electricity trade are ambiguous.*

The monopoly case studied above is clearly a special case of this and is studied next:

Assume then that the competition in the final good market is minimal, i.e. there is only on firm in each country. Given this (20) yields $\frac{\partial q^H}{\partial K} + \frac{1}{\tilde{n}^H \alpha^H}\frac{\partial D^H}{\partial K} = \frac{6}{45}\left(T^H - T^F\right) = -\frac{18}{45}\left(\frac{1}{\alpha^f} - \frac{1}{\alpha^H}\right) < 0$ by (13). We thus have

Proposition 6 *Assume that in the final good market a duopoly prevails with one firm in both countries. Then in the country exporting electricity total profits from final good and electricity production fall as electricity trade is opened if transmission capacity is small.*

The final good producers will loose in H as they have to pay higher price for the electricity while electrcity suppliers gain and n the aggregate there will be a loss of profits. Since the **SO** profits are positive it still can be the case that the welfare increases. To check for this, assume that $c'(0) = 0$. Then, using (15) and (16), the **SO** gross revenue relative to the electricity output in H is

$$\frac{\alpha^H \left(w^F - w^H\right)}{2D^H} = \frac{\frac{8}{15}\left[\left(\frac{1}{\alpha^F} - \frac{1}{\alpha^H}\right)a + \frac{\alpha^F c^F - r^F}{\alpha^F} - \frac{\alpha^H c^H - r^h}{\alpha^H}\right] + \frac{2}{15}\left(\frac{\alpha^H c^H + r^H}{\alpha^F} - \frac{\alpha^f c^f + r^F}{\alpha^H}\right)}{\frac{8}{15}\left[\frac{3}{4}a - \left(\alpha^H c^H - \frac{\alpha^F c^F}{4}\right) - \left(r^H - \frac{r^F}{4}\right)\right]} \tag{23}$$

If the final good markets is large then the expression in (23) is close to $\frac{4}{3}\left(\frac{1}{\alpha^f} - \frac{1}{\alpha^H}\right)$. Then, using (19), the welfare in H increases if $-\frac{18}{45}\left(\frac{1}{\alpha^f} - \frac{1}{\alpha^H}\right) + \theta^H \frac{4}{3}\left(\frac{1}{\alpha^f} - \frac{1}{\alpha^H}\right) > 0$, i.e. if $\theta^H \geq \frac{9}{30}\ \left(\leq \frac{1}{2}\right)$. We can thus state

Proposition 7 *In case of a duopoly final good market opening of electricity trade with small international transmission grid benefits the country exporting electricity if the size of the final good market is large enough and the marginal cost of running the transmission grid is low if the country's share in system operator's profits is large enough.*

From (19) and (23) it is clear that opening of electricity trade does not necessarily improve welfare. It is easily seen that

Proposition 8 *With duopoly in the final good market and with small capacity international transmission grid electricity trade reduces welfare in the electricity exporting country if the marginal cost of running the grid is high or if the non-electricity input costs in the country importing electricity are high relative to costs in the country exporting electricity.*

The intuition for the last part in the previous proposition is that high non-electricity input costs in the country importing electricity imply smaller international electricity price differential and hence smaller **SO** profits. **SO** profits can be made arbitrarily small by raising r^F enough.

Consider next the welfare implications of electricity trade for the importing country. For the electricity importing country the impact on welfare gross of the country's share in **SO** profits is

$$\begin{aligned}\frac{\partial q^F}{\partial K} + \frac{1}{\tilde{n}F\alpha^F}\frac{\partial D^F}{\partial K} &= \frac{M}{2}\left\{\frac{n^H}{2N} + \frac{n^H}{N} - \frac{n^H}{2\left(n^H+1\right)}\right\}T^H + \\ &\frac{M}{2}\left\{\left(\frac{n^H+1}{N}\right) + \frac{n^F n^H}{2\left(n^F+1\right)N} - 1\right\}T^F \end{aligned} \tag{24}$$

Evaluated at the duopoly final good market case (24) gives $\frac{\partial q^F}{\partial K} + \frac{1}{\tilde{n}F\alpha^F}\frac{\partial D^F}{\partial K} = \frac{6}{45}\left(T^H - T^F\right) = -\frac{18}{45}\left(\frac{1}{\alpha^f} - \frac{1}{\alpha^H}\right) < 0$, exactly the same as for the electricity exporter. Hence, we get in analogy to the exporting country:

Proposition 9 *If the final good market is a duopoly then the opening of electricity trade reduces the aggregate profits of the final good and electricity producers when the international electricity transmission capacity is small.*

In the importing country the final good producer gains from electricity trade but the electricity producers loose. With small capacity at least the electricity producer's loss outweighs the final good producer's gain. The welfare, however, depends also on **SO**'s profits. It is obvious that we can prove a result similar to Proposition 3:

Proposition 10 *With a duopoly in final good market the welfare of electricity* *importing country increases if the final good market is large enough and if the marginal cost of running the transmission grid at low grid capacity is low enough.*

Furthermore through repeating the discussion preceeding Proposition 3 we see that both countries can gain from the opening of electricity trade:

Proposition 11 *With a duopoly in the final good market both countries gain from the opening of electricity trade if the final good market is large enough, if the marginal cost of running the transmission grid is low at low grid capacity and if the* ***SO*** *profits are distributed equally enough (equal division is definitely sufficient) among the countries using the grid.*

The result analogous to Proposition 8 can obviously be proved for the electricity importing country also. More remarkable is also that welfare can decline in both countries. We record also this using the previous propositions

Proposition 12 *With a duopoly in the final god market and small capacity international transmission grid both the electicity exporting and importing country loose from opening of electricity trade if the marginal cost of running the grid is large enough.*

Before going to the cases where there can be more than one final good producer in each country it is of some interest to study what happens to the total output of final goods and electricity in the world when electricity trade is opened. Assuming that there exist equal number of final good producers in oth countries it is straightforward to calculate that the total output of final good increases since

$$\frac{\partial q^H}{\partial K} + \frac{\partial q^F}{\partial K} = \frac{M}{2N}\left(1 - \frac{\widetilde{n}}{2}\right)\left(T^F - T^H\right) > 0$$

At the same time the aggregate output of electricity falls:

$$\frac{\partial D^H}{\partial K} + \frac{\partial D^F}{\partial K} = \frac{M\widetilde{n}}{2}\left[\alpha^F\left(\frac{\alpha^H}{\alpha^F} - \frac{\widetilde{n}}{2}\right)T^H + \alpha^H\left(\frac{\widetilde{n}}{2} - \frac{\alpha^F}{\alpha^H}\right)T^F\right] < 0$$

This seemingly paradoxical result is easily understood when one remembers that electricity trade expands the final good production and hence demand for electricity in the less energy intensive country and reduces it in the energy intensive country. In this sense opening of the electricity trade clearly allows the world as a whole economize on the use of energy.

4. Electricity trade with large transmission capacity

Assume now that the transmission grid has a high capacity. Borenstein, Bushnell and Stoft (2000) have shown (see lemma 1 above) that with sufficiently high capacity the electricity firms do not have any incentives to congest the line. This leads to an equilibrium where electricity firms' decisions are not constrained by the capacity and where electricity prices are equated between countries. With sufficient capacity the electricity market equilibrium is similar to the equilibrium in the market for any input where producers are Stackelberg leaders and play Cournot game. From (10) and (11) one can solve the electricity flow that equates the prices. This gives

$$K = \frac{1}{\overline{\overline{T}}}\left[\Delta a + \frac{T^H}{\alpha^H}D^H - \frac{T^F}{\alpha^F}D^F + \frac{r^H}{\alpha^H} - \frac{r^F}{\alpha^F}\right] \tag{25}$$

where $\triangle \equiv \frac{1}{\alpha^F} - \frac{1}{\alpha^H}$, $\overline{T} \equiv \frac{T^H}{\alpha^H} + \frac{T^F}{\alpha^F}$. Substituting this back to (10) gives the inverse demand for electricity with high transmission capacity:

$$w^{uc} = \frac{\frac{T^H + T^F}{\alpha^H\alpha^F}}{\overline{T}}a - \left(\frac{1}{\alpha^H\alpha^F} + \frac{\frac{T^H T^F}{\alpha^H\alpha^F}}{\overline{T}}\right)\left(D^H + D^F\right) - \frac{\frac{T^F}{\alpha^F}}{\overline{T}}\frac{r^H}{\alpha^H} - \frac{\frac{T^H}{\alpha^H}}{\overline{T}}\frac{r^F}{\alpha^F} \tag{26}$$

It is worthwhile here to note that Using this the Cournot outputs of the electricity producers are

$$D^j = \frac{A - 2c^j + c^k}{3\widehat{T}}, k \neq j \tag{27}$$

where $A \equiv \frac{\frac{T^H + T^F}{\alpha^H \alpha^F}}{\overline{T}} a - \frac{\frac{T^F}{\alpha^F}}{\overline{T}} \frac{r^H}{\alpha^H} - \frac{\frac{T^H}{\alpha^H}}{\overline{T}} \frac{r^F}{\alpha^F}$, and $\widehat{T} \equiv \frac{1}{\alpha^H \alpha^F} + \frac{\frac{T^H T^F}{\alpha^H \alpha^F}}{\overline{T}}$. The final good firm's output is

$$q^j = \frac{a - \left[\left(n^k + 1\right) \alpha^j - n^k \alpha^k\right] w^{uc} - \left(n^k + 1\right) r^j + n^k r^k}{N}$$

where w^{uc} is given by (26) and (27). Since with uncosntrained transmission capacity there is no need for a system operator country j's welfare is

$$U^j = n^j \left(q^j\right)^2 + \widehat{T} \left(D^j\right)^2 \tag{28}$$

The welfare impacts of electricity trade are ambiguous. This can be understood by remembering what happens in the original Brander-Spencer -model as in the previous section.

To make the point on the ambiguity of the welfare implications clear let us consider the case where there is only one H and F final good producer. It is straightforward to show that the welfare without electricity trade is in H (analogous equation holds for F) by

$$U^{HNT} = \frac{3}{\alpha^2} \left[\frac{4}{\left(\alpha^F\right)^2} \left(G_1 - c^H\right) - \frac{1}{\alpha \alpha^F} \left(G_2 - c^F\right) \right]^2 \tag{29}$$

and with trade

$$U^{HT} = \left[\frac{B^H}{3} - \frac{\left(2\alpha^H + \alpha^F\right)}{3} \frac{\left(\widehat{B} + c^H + c^F\right)}{3} \right]^2 + \widehat{T} \left[\frac{\widehat{B} - 2c^H + c^F}{3\widehat{T}} \right]^2 \tag{30}$$

where $B^j \equiv a - 2r^j + r^k$, k $\neq$ j, $G_1 \equiv \frac{2B^H+B^F}{\alpha^H}$, $G_2 \equiv \frac{2B^F+B^H}{\alpha^F}$, $\widehat{B} \equiv \frac{\frac{T^F}{\alpha^F}}{\overline{T}} G_1 + \frac{\frac{T^H}{\alpha^H}}{\overline{T}} G_2$. Then using (29) and (30) it can be shown that welfare can either increase or decrease when electricity trade is opened.

The ambiguity of the welfare implications can be understood by comparing the pricing of electricity without trade with pricing when capacity is abundant. The inverse demand curve facing H electricity producer without trade is given by (5) while with unconstrained capacity it is given by (10) together with (25) resulting in (26). With the help of these equations (26) can be rewritten as

$$w^{uc} = \frac{a - r^H}{\alpha^H} + \tau_3 + \left(-\frac{2}{\left(\alpha^H\right)^2} + \tau_1 \right) D^H - \left(\frac{1}{\alpha^F \alpha^H} + \tau_2 \right) D^F \tag{31}$$

where $\tau_1 \equiv \frac{\left(\frac{T^H}{\alpha^H}\right)^2}{\overline{T}}$, $\tau_2 = \frac{\frac{T^F T^H}{\alpha^F \alpha^H}}{\overline{T}}$, and $\tau_3 = \frac{\frac{T^H}{\alpha^H}}{\overline{T}} \left[\triangle a + \left(\frac{r^H}{\alpha^H} - \frac{r^F}{\alpha^F} \right) \right]$. Comparing (5) and (31) reveals that electricity trade has 3 three different types of impacts on the (inverse) demand facing the exporter of the electricity: First, it widens the market (demand function shifts up), secondly it reduces the impact of exporter's own production on electricity price (the usual competitive effect), and thridly it increases the impact of foreign competitor's production on the demand facing the exporter (demand function shifts down) by increasing the substitutability in demand between the electricity supplied from different locations. The first two effects tend to expand the exporter's electricity production while the third tends to reduce it. The third effect is crucial: with transmission capacity constraints the electricities provided from different locations are imperfect substitutes while with sufficient transmission capacity supplies from different locations are perfect substitutes as electricity is a homogenous good by its physical nature. The net effect of electricity trade on exporter's production is thus ambiguous. As an example consider the case where $r^j = c^j = 0$. Then from (7) and (27) we get

$$\begin{aligned} D^H &= \frac{\alpha^F + \alpha^H}{9} a = D^F \equiv D^T \\ D^{HNT} &= \frac{\alpha^H}{5} a \end{aligned} \tag{32}$$

Hence, electricity production by the electricity exporter expands (contracts) with the trade as $\frac{\alpha^F}{\alpha^H} > (<) \frac{4}{5}$. This is an effect that was not possible in case of trade with small transmission capacity.

It is obvious that similar decomposition as was done for the electricity exporter can be made for the importer giving:

$$w^{uc} = \frac{a - r^F}{\alpha^F} - \mu_3 + \left(-\frac{2}{(\alpha^F)^2} + \mu_1 \right) D^F - \left(\frac{1}{\alpha^F \alpha^H} + \tau_2 \right) D^H$$

where $\mu_1 = \frac{\left(\frac{\tau^F}{\alpha^F}\right)^2}{\overline{T}}$, and $\mu_3 = \frac{\frac{\tau^H}{\alpha^H}}{\overline{T}} \left[\triangle a + \left(\frac{r^H}{\alpha^H} - \frac{r^F}{\alpha^F} \right) \right]$. The interesting effect here is that from point of view of the electricity producer in the importing country the opening of trade with no transmission capacity constraints implies that the market size definitely contracts (demand curve shifts down). Yet, using the same example as for the exporter ($r^j = c^j = 0$) it is easily seen the production of electricity in the country importing expands when trade with sufficient transmission capacity is opened. This again contrasts with the case of electricity trade with small transmission capacity. The intuition here is that with small transmission capacity the producer in the importing country adjusts passively to the aggressive exports while with large transmission capacity it can respond aggressively. Hence we get

Proposition 13 *The production of the electricity exporter can contract and the electricity production in the importing country can expand when electricity trade* *with large transmission capacity is opened.*

To understand the welfare effects one also should look at the electricity prices. In the specific example we have used the electricity prices without electricity trade are (from (8))

$$\begin{aligned} w^{HNT} &= \frac{2}{5\alpha^H} a \\ w^{FNT} &= \frac{2}{5\alpha^F} a \end{aligned} \tag{33}$$

With unconstrained transmission capacity the unified electricity price is[3]

$$w^{uc} = \frac{D^T}{\widehat{T}} \tag{34}$$

It is straightforward to show that $w^{uc} > w^{HNT}$ if the energy intensity of production is high enough in both countries and the reverse holds if the energy intensity is low enough in both countries. In the first case final good producers in H are definitely hurt by the electricity trade and the overall welfare will decline if also the electricity production in H contracts. In F on the other hand welfare will improve. But it is also possible to see a lower unified electricity price than prevailed in autarky. In this case both countries can benefit from trade.

5. Concluding comments

The paper uses recent models of electricty trade to model the implications of international electricity trade. I have argue that opening of international electricity trade has ambiguous welfare implications and can be welfare deteriorating. The result is obtained in a model that extends the well-known Brander-Spencer (1985) model to include electricity as an input to final good production. In that context the result may seem obvious as users of electricity will be hurt by the increase in price if initially they have been enjoying from low prices. One may still wonder where the result comes from since in principle electrcity price change is just a transfer of income between producers. Here the strategic aspects known from the Brander-Spencer -model are important. An increase in the electricity price works like an export tax on final good producers in contrast to the export subsidy that is optimal in the Brander-Spencer -model. The electricity price increase shifts rents to other countries that are not recouped by the electricity supplier. The implication is that the welfare implications of the electricity market opening are unclear and there is a possibility that one of the countries at the least experiences welfare loss. All these results depend on the degree of competitiveness in the markets and on the international differences in energy intensity of production. An important twist in the results is that also the international distribution of final good producers matters for the welfare, not only their total number. It is exactly this that allows to balance between electricity producers and final good producers profits in both countries and makes it possible for both countries to gain from the possible rents the opening of trade creates.

I have ignored many important aspects that should at some point be incorporated in the analysis. Among them is the assumption that I have not taken into account pure domestic sources of electricity demand, I have assumed that all demand comes from exporting firms. In this case welfare implications are clear, however, and do not reverse the result on ambiguity. I have also assumed that the transmission capacity is exogenously given. Clearly it is an important extension to endogenize the capacity. The most serious omission is the response of other input prices to changes in electricity prices. Electricity price changes have an impact on the demands for other inputs and thus on their prices. These impacts can be analyzed only in a truly general equilibrium model. I leave the construction of such a model for future.

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TO BE COMPLETED

Notes

[1] In this paper I ignore the household demand for electricity.

[2] The solution to the Cournot game when there are several suppliers with market power at both ends of the transmission line has not been worked out. The case with one producer at each end has been studied by Borenstein et. al. (2000), the case with two producers at the same end has been studied by willems (2002).

[3] The unified electricity price is $A - 2\widehat{T}D^T$ and $D^T = \frac{A}{3\widehat{T}}$ giving the formula.