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Electrified Trade

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Abstract

International unification of national electricity markets may be economically one of the most important steps in reduction of trade barriers. In international context electricity markets have implications for the performance of export firms. The Brander-Spencer - market share rivalry model is here extended by including electricity production (used by exporters) and competition between electricity producers to study the effects of international deregulation of electricity markets. In the model electricity producers behave strategically vis a vis each other even without international transmission lines because electricity demand is derived demand. This aspect is ignored in the standard models of electricity markets. 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 producing final good between countries. When the international electricity transmission capacity is small both countries may gain or lose from electricity trade depending on aggregate rents the market unification creates. E.g. with equal number of final good firms in both countries the aggregate profits in both countries decline when electricity trade is opened. The revenue of the system operator of the transmission grid may also play crucial role. The ambiguity of welfare effects carries over to the case of large transmission capacity. Electricity trade can improve global energy efficiency: global electricity production can even decline with trade while simultaneously the production using it as an input increases.

JEL Classification: F1, L1, L9

Keywords: Electricity trade, transmission capacity, strategic trade

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1. Introduction

Electricity markets have faced a period of deep deregulation in many parts of the world. Notable examples are Nordic countries, UK and USA. A remarkable component of deregulation in many cases has been the unification of national and regional markets. 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.

Traditionally in open economies policy makers have been concerned with the profitability of the export firms, i.e. with market share rivalry. Before deregulation electricity was supplied in many countries by state owned monopolies or near monopolies whose prices were regulated partly to improve the competitiveness of domestic firms. This concern is still high on the agenda. E.g. recently Finnish government decided to give permission to build a new nuclear power plant in order to keep electricity prices low for the Finnish export sector. Deregulation has also at least partly been motivated by the desire to decrease electricity prices.

Market share rivalry in international markets and its policy implications were first studied by Brander and Spencer (1985). I modify the Brander-Spencer model to incorporate electricity trade in a two-tier strategic trade model with electricity production in the first tier and export production in the second tier. The model is 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 main result of the paper is that the welfare effects (which here are equivalent to changes in aggregate profits of the firms) of electricity market unification are not clear. E.g. when electricity trade is opened but the transmission lines have a low capacity electricity 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 lose simultaneously when electricity trade is opened. The profits (originating from congestion charges imposed on electricity firms) 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 but the welfare implications are ambiguous, in general.

The strategic relationships in the Brander-Spencer model imply that electricity price changes have effects beyond pure transfers between consumers and producers of electricity. An interesting aspect here is that though within countries the interests of the electricity producers and producers using electricity differ the interests are partially shared due to international linkages. E.g. if those firms getting access to lower electricity prices are able to increase their profits to such an extent that aggregate rents from foreign markets increase then both countries can benefit. This 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. This result may also help to understand why the unification of Nordic electricity markets is widely regarded as a success. In Finland and Sweden the major electrcity users are forest and metal industries and especially in forest industry the number of firms in both countries are roughly similar. Hence, unification of only Finnish and Swedish markets might not have been welfare improving. In contrast, the structure of Norwegian exports differs from Finnish and Swedish exports making welfare gains possible.

With electricity markets several aspects due to the physical nature of the commodity traded must be considered. International trade in electricity requires transmission lines whose capacity is crucial for the strategic behavior of the firms. 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.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, see also Skaar and Sørgard 2002) 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. Secondly, 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[2] 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 within their own countries 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. Thus, without electricity trade electricity firms are engaged in market share competition through domestic export firms, with trade through export firms in both countries.

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 Sanyal and Jones (1980) to economic geography (Fujita and Thisse 2001) and raising questions on firm strategies like vertical foreclosure (Jones and Spencer 1991) and foreign

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

[2]Aune, Golombek, Kittelsen, and Rosendahl (2001) in a computable general equilibrium model derive electricity demand explicitly from consumer and firm optimization problems. They also provide references to other CGE-models with trade in electricity. In these models energy markets are assumed to be competitive while I here want to focus on the case of imperfect competition, the issue most often discussed otherwise in the literature. Amundsen and Bergman (2002) is an example of a numerical model of electricity trade with imperfectly competitive electricity suppliers where demand for electricity is not derived from endusers behavior.

In von der Fehr and Sandsbråten (1997) the issue is on trade in electricity when electricity in different countries is produced with different technologies. Also in this model the demand for electricity is specified in an ad hoc manner.

direct investment (Markusen 2002). 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.

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.

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 $D^j = \alpha^j n^j q^j$. In the tradition of the electricity market analysis I 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 no 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 users 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) and has not been worked out analytically in the literature. 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 note 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:

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

where it is clear that $M\left(1-\frac{\widetilde{n}^H\widetilde{n}^F}{2}\right) < 1$. Note 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 since it increases demand by domestic firms since they are able to expand their production.

3. Electricity trade with small transmission capacity

Assume now that an electricity transmission grid with capacity K is installed. With the grid the final good producers in both countries can buy electricity from both countries. How much trade there is depends on the transmission capacity and on the strategies the electricity firms use. 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. This differential can be due either to the lower cost of producing electricity in H than in F or due to smaller electricity intensity of production in F than in H (see below). It is straightforward to calculate (from (8)) that a reduction in c^H and an increase in c^F increases the price differential if

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

which is 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. In addition the constraint

$$\widetilde{n}^H < \frac{\alpha^F}{\alpha^H}, \widetilde{n}^F < \frac{\alpha^H}{\alpha^F} \tag{10}$$

is imposed to make its sure that an increase in the transmission capacity reduces the price differential for given levels of electricity production (see below). Clearly, if (10) holds then also (9) is automatically satisfied. We assume that (10) 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. Finally, I also assume that

$$\alpha^F < \alpha^H \tag{11}$$

If the final good market is large (a is large) then, ceteris paribus, 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 (from (8)). The previous three assumptions guarantee that the autarky electricity price is lower in H than in F if in F marginal cost of production is not larger than in F and/or final good market is large enough.

I assume that the local retail grid is owned by the electricity companies and that the costs of maintaining the grid are included in c^j[3]. I assume that the main grid and here especially the grid connecting the two countries electricity markets is owned by a separate company. If the transmission capacity is small then the one must specify how the capacity is allocated between producers. The usual assumption to which I stick here is that the grid is owned and controlled[4] by a system operator (**SO**) whose task is to allocate the transmission rights and charging the electricity suppliers for utilizing the grid. I assume that the **SO** aims at efficient use of the grid. One way to achieve this is nodal pricing (see e.g. Borenstein, Bushnell and Stoft 2000, Joskow and Tirole 2000, 2003)[5]. 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

[3]E.g. in Finland the electricity companies are allowed to charge so called transmission charge from consumers. The charge is supposed to cover (with "reasonable" margin) only the costs of transmission. The formulation used in this paper is a stylized version of this practice. One could also think of companies getting a share of the system operator's (SO) (see below) profits to encourage investment in the grid capacity (see Joskow and Tirole 2003 for a discussion).

[4]There exist cases where **SO** does not own the grid.

[5]Joskow and Tirole (2003) show that if electricity firms have market power and congestion charges are returned back to firms to encourage investment in transmission capacity then nodal pricing may not be efficient. Joskow and Tirole (2000) argue that if the electricity firms have market power then the possibility for them to own physical or financial rights to the grid (and thus to **SO** profits) their market power is enhanced. E.g. the Finnish main grid is owned and operated by Finngrid, a regulated monopoly, which is partly owned by the largest electricity companies. In this paper I assume for simplicity that they do not have these rights. Joskow and Tirole show that this can be socially optimal. Nothing in the analysis would change if the firms owned the rights but would not take into account the impacts of their own actions to these profits.

price prevailing at the node where they are located. This holds since the **SO** imposes a congestion charge on the users of the transmission grid. The efficient charge is equal to the price differential at different nodes. 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 international electricity price differential. From (5) one gets for H price

$$w^H = \frac{a}{\alpha^H} - \frac{\left(D^H - K\right)}{\widetilde{n}^H \left(\alpha^H\right)^2} - \frac{\left(D^F + K\right)}{\alpha^H \alpha^F} - \frac{r^H}{\alpha^H} \tag{12}$$

and likewise for F:

$$w^F = \frac{a}{\alpha^F} - \frac{\left(D^F + K\right)}{\widetilde{n}^F \left(\alpha^F\right)^2} - \frac{\left(D^H - K\right)}{\alpha^H \alpha^F} - \frac{r^F}{\alpha^F} \tag{13}$$

The physical nature of the electricity transmission raises strategic issues not encountered in more common models. E.g. if transmission capacity is small then a firm can congest the grid for the firm in the other end of the line by not selling electricity to the other direction as the capacity constrains only the net trade flows. Borenstein, Bushnell and Stoft (2000) have characterized the possible equilibria in game when there exists only one supplier at each end of the line but where there is no indirect competition between electricity firms without the grid (as is the case here). Their result can, however, be easily transferred to the present model and is 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.*

From this paper's point of view the interesting result concerns the equilibrium with very small transmission capacity. Hence, I'll sketch the proof for that case. Since we have assumed that $w^H < w^F$ without transmission line the H electricity supplier will always supply to F as much electricity as the transmission capacity allows. The F electricity producer has two alternatives. The first is to adapt passively to the supply K by the H producer implying that $w^H < w^F$ also after electricity trade is opened. Its profits will decline relative to the autarky level but the loss decreases as K becomes small and will disappear in the limit. The second alternative open to the F producer is to behave aggressively and expand its production above the autarky level so much that $w^F \leq w^H$ (as for higher prices in F there electricity would only flow from H to F and the F firm would passively adapt to it). It has to do that for *all* transmission capacities, no matter how small they are. Thus, the second strategy produces losses relative to autarky even for infinitesimal transmission capacities while the loss with passive strategy would be infinitesimal. Hence, for small capacities the first, passive strategy, is optimal and in equilibrium H firm exports K units of electricity to F and F firm takes adjusts passively to it.

In the unconstrained equilibrium electricity price is unified and the model reduces to a standard model of vertical competition with Cournot-competition at both stages. In the congestion equilibrium electricity prices differ across markets and electricity firms have limited power to compete directly for the clients.

Only the congestion and unconstrained equilibria are studied here. 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.

With nodal pricing the profits of the electricity producers are (see also footnote 5)

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

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 (10). 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 $c^o(K)$ 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 (see also footnote 5)

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

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

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

The main result of the paper can now be given:

Proposition 2 *Both the countries exporting and importing electricity gain 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 both countries if **SO** profits are small enough.*

Proof. See the Appendix. ■

The limits imposed by conditions a) and b) in the proposition are quite tight for the welfare gains to be certain. 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[6]. 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 electricity exporting country are smaller the larger the number of firms located there as they receive larger share of the profit.

The most surprising aspect in Proposition 2 is that the conditions guaranteeing welfare improvement for both countries are identical. The intuition here is that for both countries to gain the aggregate surplus that can be extracted from foreign consumers must increase. Since this must happen through foreign producers (who gain from the decline in the electricity price) whose increased demand for H electricity then distributes some of the rents to H the conditions for the welfare improvement must be the same. Foreign producers can increase the total rent that can be earned from the export markets because they are assumed to be less energy intensive (11). Electricity trade allows them to buy electricity at lower prices.

Proposition 2 also indicates that welfare in both countries can decline if **SO** profits are small enough. Electricity prices do not depend on the marginal cost of the **SO**, $(c^o)'(0)$. Hence, the larger the marginal cost at small capacities the more likely it is that welfare declines globally. But **SO** profits can be large enough to improve welfare globally even if aggregate profits decline otherwise. This can be shown in the case where there is duopoly in the final good market.

The case of an international duopoly is easily analyzed on the basis of Proposition 2:

[6] It is straightforward to show that the sensitivity of H final good producers' profits to changes in the price of electricity declines when n^H increases. Similarly, F final good producers' aggregate profits are largest when $n^F = 1$.

Proposition 3 *Assume that in the final good market a duopoly prevails with one firm in both countries. Then in both of the countries total profits from final good and electricity production fall as electricity trade is opened if transmission capacity is small.*

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

$$\frac{\alpha^H\left(w^F - w^H\right)}{2D^H} = \tag{19}$$

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

If the final good markets is large then the expression in (19) is close to $\frac{4}{3}\left(\frac{1}{\alpha^f} - \frac{1}{\alpha^H}\right)$. Then, using (30) (see the appendix), 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 $\theta^H \geq \frac{9}{30}\ \left(\leq \frac{1}{2}\right)$. Similar calculations can be repeated for the importing country and one gets

Proposition 4 *In case of a duopoly final good market opening of electricity trade with small international transmission grid benefits both countries 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.*

Finally, it is of 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 both 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. We record this in

Proposition 5 *When international electricity trade with small international capacity is opened it is possible that total electricity output declines while total output of the good needing electricity increases. Trade thus increases aggregate energy efficiency in the world.*

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 (12) and (13) one can solve the electricity flow that equates the prices. This gives

$$K = \frac{1}{\overline{\overline{T}}}\left[\Delta a + \frac{T^H}{\alpha^H}D^H - \frac{T^F}{\alpha^F}D^F + \frac{r^H}{\alpha^H} - \frac{r^F}{\alpha^F}\right] \tag{20}$$

where $\triangle \equiv \frac{1}{\alpha^F} - \frac{1}{\alpha^H}$, $\overline{\overline{T}} \equiv \frac{T^H}{\alpha^H} + \frac{T^F}{\alpha^F}$. Substituting this back to (12) gives the inverse demand for electricity with high transmission capacity:

$$w^{uc} = \frac{\frac{T^H+T^F}{\alpha^H\alpha^F}}{\overline{\overline{T}}}a - \left(\frac{1}{\alpha^H\alpha^F} + \frac{\frac{T^HT^F}{\alpha^H\alpha^F}}{\overline{\overline{T}}}\right)\left(D^H + D^F\right) - \frac{\frac{T^F}{\alpha^F}}{\overline{\overline{T}}}\frac{r^H}{\alpha^H} - \frac{\frac{T^H}{\alpha^H}}{\overline{\overline{T}}}\frac{r^F}{\alpha^F} \tag{21}$$

Using this the Cournot outputs of the electricity producers are

$$D^j = \frac{A - 2c^j + c^k}{3\widehat{T}}, k \neq j \tag{22}$$

where $A \equiv \frac{\frac{T^H+T^F}{\alpha^H\alpha^F}}{\overline{\overline{T}}}a - \frac{\frac{T^F}{\alpha^F}}{\overline{\overline{T}}}\frac{r^H}{\alpha^H} - \frac{\frac{T^H}{\alpha^H}}{\overline{\overline{T}}}\frac{r^F}{\alpha^F}$, and $\widehat{T} \equiv \frac{1}{\alpha^H\alpha^F} + \frac{\frac{T^HT^F}{\alpha^H\alpha^F}}{\overline{\overline{T}}}$. 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 (21) and (22). Since with uncosntrained transmission capacity there is no need for a system operator country j's welfare is

$$U^j = n^j\left(q^j\right)^2 + \widehat{T}\left(D^j\right)^2 \tag{23}$$

The welfare impacts of electricity trade are ambiguous. The intuition (based on the original Brander-Spencer story) is the same as in the previous section. To make the point 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

$$U^{HNT} = \frac{3}{\alpha^2}\left[\frac{4}{\left(\alpha^F\right)^2}\left(G_1 - c^H\right) - \frac{1}{\alpha\alpha^F}\left(G_2 - c^F\right)\right]^2 \tag{24}$$

and with trade

$$U^{HT} = \left[\frac{B^H}{3} - \frac{\left(2\alpha^H + \alpha^F\right)}{3}\frac{\left(\widehat{B} + c^H + c^F\right)}{3}\right]^2 + \widehat{T}\left[\frac{\widehat{B} - 2c^H + c^F}{3\widehat{T}}\right]^2 \tag{25}$$

where $B^j \equiv a - 2r^j + r^k$, k $\neq$ j, $G_1 \equiv \frac{2B^H + B^F}{\alpha^H}$, $G_2 \equiv \frac{2B^F + B^H}{\alpha^F}$, $\widehat{B} \equiv \frac{\frac{T^F}{\alpha^F}}{T} G_1 + \frac{\frac{T^H}{\alpha^H}}{T} G_2$. Then using (24) and (25) 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 (12) together with (20) resulting in (21). With the help of these equations (21) can be rewritten as

$$w^{uc} = \frac{a - r^H}{\alpha^H} + \tau_3 + \left(-\frac{2}{(\alpha^H)^2} + \tau_1 \right) D^H - \left(\frac{1}{\alpha^F \alpha^H} + \tau_2 \right) D^F \tag{26}$$

where $\tau_1 \equiv \frac{\left(\frac{T^H}{\alpha^H}\right)^2}{T}$, $\tau_2 = \frac{\frac{T^F T^H}{\alpha^F \alpha^H}}{T}$, and $\tau_3 = \frac{\frac{T^H}{\alpha^H}}{T} \left[\triangle a + \left(\frac{r^H}{\alpha^H} - \frac{r^F}{\alpha^F} \right) \right]$. Comparing (5) and (26) reveals that electricity trade has 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 thirdly, 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 (22) we get

$$\begin{aligned} D^H &= \frac{\alpha^F + \alpha^H}{9} a = D^F \equiv D^T \\ D^{HNT} &= \frac{\alpha^H}{5} a \end{aligned} \tag{27}$$

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 $\mu_1 = \frac{\left(\frac{T^F}{\alpha^F}\right)^2}{T}$, and $\mu_3 = \frac{\frac{T^H}{\alpha^H}}{T} \left[\triangle a + \left(\frac{r^H}{\alpha^H} - \frac{r^F}{\alpha^F} \right) \right]$. 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 6 *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))

$$\begin{aligned} w^{HNT} &= \frac{2}{5\alpha^H}a \\ w^{FNT} &= \frac{2}{5\alpha^F}a \end{aligned} \tag{28}$$

With unconstrained transmission capacity the unified electricity price is[7]

$$w^{uc} = \widehat{T}D^T \tag{29}$$

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 electricity 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 electricity 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

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

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. Finally, an interesting result was that electricity trade can lead to reduced global production of electricity even when global production using electricity as an input expands. This holds since electricity will flow to the country where the energy intensity of production is lower as in that country electricity prices without trade are lower. Another way to put the result is to say that electricity trade improves the global energy efficiency of production.

I have ignored many important aspects that could at some point be incorporated in the analysis. Among them is the assumption that I have ignored the demand for electricity by domestic consumers and firms producing only for local consumption, I have assumed that all demand comes from exporting firms. In this case the welfare implications of electricity trade still seem ambiguous using the same logic as in this paper. I have also assumed that the transmission capacity is exogenously given. Clearly it is important to endogenize the capacity[8]. Among 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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7. Appendix

Proof of Proposition 1: 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:

$$\frac{\partial q^H}{\partial K} + \frac{1}{\widetilde{n}^H \alpha^H} \frac{\partial D^H}{\partial K} + \frac{\theta^H \left[\left(w^F - w^H \right) - \left(c^o \right)' (0) \right]}{\frac{2D^H}{\alpha^H}} \tag{30}$$

The first term in (30) 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 electricity 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 (30) can be collected to yield (using (3), (12), and (15))

$$\frac{\partial q^H}{\partial K} + \frac{1}{\widetilde{n}^H \alpha^H} \frac{\partial D^H}{\partial K} = \frac{M}{2} \left\{ -\frac{n^F + 1}{N} - \frac{n^H n^F}{2 \left(n^H + 1 \right) N} + 1 \right\} T^H + \frac{M}{2} \left\{ -\frac{n^F}{2N} - \frac{n^F}{N} + \frac{n^F}{2 \left(n^F + 1 \right)} \right\} T^F \tag{31}$$

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 (remember that given (10) and (11) 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 (31)) that

$$\frac{\partial q^H}{\partial K}+\frac{1}{\widetilde{n}^H\alpha^H}\frac{\partial D^H}{\partial K}= \tag{32}$$
$$\frac{Mn^H}{2N\left(n^H+1\right)}\left[2\left(n^H+1\right)-n^F\right]T^H+\frac{Mn^F}{4}\left(-\frac{3}{N}+\frac{1}{n^F+1}\right)T^F$$

Similarly for the importing country one calculates

$$\frac{\partial q^F}{\partial K}+\frac{1}{\widetilde{n}F\alpha^F}\frac{\partial D^F}{\partial K}=\frac{M}{2}\left\{\frac{n^H}{2N}+\frac{n^H}{N}-\frac{n^H}{2\left(n^H+1\right)}\right\}T^H+ \tag{33}$$
$$\frac{M}{2}\left\{\left(\frac{n^H+1}{N}\right)+\frac{n^Fn^H}{2\left(n^F+1\right)N}-1\right\}T^F$$

giving after simplification

$$\frac{\partial q^F}{\partial K}+\frac{1}{\widetilde{n}F\alpha^F}\frac{\partial D^F}{\partial K}= \tag{34}$$
$$\frac{Mn^H}{4}\left(\frac{3}{N}-\frac{1}{n^H+1}\right)T^H+\frac{Mn^F}{4N\left(n^F+1\right)}\left[n^H-\left(2n^F+1\right)\right]T^F$$

(32) and (34) reveal that aggregate profits in both countries 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 countries also share in the **SO** profits we get the Proposition 1.