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## Working Paper Renewable Electricity Policy and Market Integration

IFN Working Paper, No. 968

**Provided in Cooperation with:** Research Institute of Industrial Economics (IFN), Stockholm

*Suggested Citation:* Tangerås, Thomas (2013) : Renewable Electricity Policy and Market Integration, IFN Working Paper, No. 968, Research Institute of Industrial Economics (IFN), Stockholm

This Version is available at: https://hdl.handle.net/10419/81408

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IFN Working Paper No. 968, 2013

# **Renewable Electricity Policy and Market** Integration

Thomas P. Tangerås

Research Institute of Industrial Economics P.O. Box 55665 SE-102 15 Stockholm, Sweden info@ifn.se www.ifn.se

## **Renewable electricity policy and market integration**<sup>\*</sup>

by

**Thomas P. Tangerås** 

(www.ifn.se/thomast)

Research Institute of Industrial Economics (IFN) Box 55665, 102 15 Stockholm, Sweden

June 27, 2013

#### Abstract

I analyze renewable electricity policy in a multinational electricity market with transmission investment. If national policy makers choose support schemes to maximize domestic welfare, then a trade policy motive arises operating independently of any direct benefit of renewable electricity. The model predicts electricity importing (exporting) countries to choose policies which reduce (increase) electricity prices. A narrow pursuit of domestic objectives distorts transmission investment, thereby market integration, below the efficient level. Distortions cannot be corrected by imposing national renewable targets alone. Instead, subsidies to transmission investment and a harmonization of and reduction in the number of policy instruments can improve welfare.

*Keywords*: Market integration, renewable electricity, trade policy, transmission investment. *JEL Codes*: D23, F15, Q48, Q56.

<sup>&</sup>lt;sup>\*</sup> Many thanks to Henrik Horn, Jonas Teusch, Bert Willems and seminar/conference participants at IFN, SNEE (Mölle) and MEC (Mannheim) for their helpful comments. This research was financed within the IFN program "The Economics of Electricity Markets" (<u>www.ifn.se/eng/research/the economics of electricity markets</u>).

#### 1. Introduction

A cornerstone of EU energy policy is to create a well-functioning European internal market for electricity. Another fundamental objective is to transform the EU into an economy based upon a reliable and environmentally sustainable supply of energy.

To facilitate the transformation into a greener economy, the EU has imposed binding national targets for the renewable share of energy consumption, but delegates to the individual member states how to fulfill them (Directive 2009/28/EC). Electricity makes up a significant share of final energy consumption; the EU average is roughly 20 per cent.<sup>1</sup> To achieve the renewables targets, many EU member states thus have implemented policies to promote the production of electricity from renewable energy sources, *RES-E*.

RES-E support mechanisms now are main drivers of investments in new generation capacity in many countries and thereby exercise a substantial influence over electricity wholesale prices. Prices affect not only generation and consumption, but also transmission. Network owners earn a congestion rent on buying electricity in one country and selling it at a higher price in another. RES-E support affects the profitability of expanding transmission capacity through its effect on electricity prices and congestion rent. The capacity of cross-border transmission lines in turn determines the degree of market integration by limiting the volume of electricity trade between countries. Hence, RES-E support and market integration are linked through the electricity market.

This paper explores the connection between RES-E policies and market integration in the framework of a multinational electricity market with transmission investment.<sup>2</sup> A key result is that the twin goals of increased RES-E production and market integration may oppose one another when implementation is decentralized to the individual member states.

In an electricity importing country, support mechanisms such as certificates and feed-in-tariffs boost investment in domestic renewable generation and drive down the import price of electricity. This yields a positive terms-of-trade effect whereby domestic consumers obtain cheaper electricity. In an electricity exporting country, RES-E policies such as a production tax on non-renewable electricity increase the export price of electricity. This represents a positive terms-of-trade effects whereby domestic producers earn higher profit. Countries thus have incentives to implement RES-E policies for trade policy reasons even if policy makers

<sup>&</sup>lt;sup>1</sup> See <u>http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main\_tables</u>.

 $<sup>^{2}</sup>$  This is a model of market integration between jurisdictions, where each jurisdiction unilaterally decides its RES-E policy. Here, these jurisdictions are countries, but one could equally well assume them to be states such as in the U.S.

place no value on RES-E itself. Domestic policies drive down cross-border price differences and congestion rent, which lowers transmission investment and market integration.

Decentralized RES-E policies reduce overall welfare in an otherwise well-functioning market by distorting consumption, production and transmission investment. An apparent solution would be to correct distortions by imposing appropriate renewables targets on each country, as is currently done in the EU. But binding targets are insufficient to eliminate trade policy. The electricity importing (exporting) country could suppress import (inflate export) prices, by taxing electricity consumption (non-renewable electricity production). Both countries could achieve their RES-E targets by a feed-in tariff with a cap on total revenue (price plus tariff).

Ulterior motives such as trade policy thus can explain why countries, or groups of countries in a global context, find it beneficial to implement renewables policies even when these policies seem incapable of correcting any obvious environmental or other externality. Trade policy can also explain why countries sometimes introduce multiple instruments to achieve what appears to be a single objective, RES-E production in this case.

RES-E support mechanisms, as pursued by the EU and elsewhere, largely focus on incentives to invest in renewable generation. But decentralized policies distort prices, so congestion rent underestimates the marginal social benefit of transmission. Hence, subsidies to transmission increase welfare under decentralized policy making, even if electricity prices remain distorted.

Harmonization of RES-E policies and a reduction in the set of available instruments is another way of increasing market efficiency by limiting the scope for trade policy. A possibility is to create an integrated certificate market, following the example of the joint Swedish-Norwegian certificate market. Free certificate trade improves efficiency by reallocating renewable investment to its most socially beneficial location.

The literature on RES-E policies mostly assumes away transmission constraints (e.g. Jensen and Skytte, 2002; Fischer and Newell, 2008; Böhringer and Rosendahl, 2010; Fischer, 2010; Fischer and Preonas, 2010), even those studying multinational markets (e.g. Amundsen and Mortensen, 2001; Morthorst, 2003; del Río, 2005; Unger and Ahlgren, 2005; Söderholm, 2008; Amundsen and Bergman, 2012). Traber and Kemfert (2009) are an exception, but they treat transmission constraints as exogenous. None of the above deliver predictions regarding RES-E policies, transmission investment and market integration. What is more, they all take policies as given. I analyze national policy makers' incentives for introducing different types

of renewables policies. Ogawa and Wildasin (2009) find decentralized policy making to be efficient. However, their result depends crucially upon the assumption of policy makers treating electricity prices as exogenous. If policy makers instead take the price effect of policies into account, then decentralized policy making generally is inefficient. This paper relates to a trade literature recognizing how governments may pursue substitute policies when trade agreements prevent governments from using tariffs and export subsidies directly; see Copeland (1990) for the seminal contribution. RES-E support schemes represent a substitute in the present context, and I develop empirical predictions regarding their design. Market integration (transmission capacity) here is endogenous and imperfect, while the trade literature generally considers the case of perfect integration.<sup>3</sup>

The remainder of this paper is organized as follows: Section 2 analyzes the effects on prices, production, transmission investment and welfare of introducing certificates in a multinational electricity market. Section 3 analyzes RES-E targets and considers corrective policies for transmission investment in a market with positive RES-E externalities. Section 4 studies the properties of an integrated certificate market. Section 5 concludes with a discussion of the robustness of the results. The analysis in the main body of the text rests upon an informal graphical exposition of the model. The full model specification and mathematical proofs are relegated to the Appendix.

### 2. Certificates in a multinational electricity market

Certificates, or renewable portfolio standards, are a common policy instrument for promoting production of electricity from renewable energy sources. Producers earn certificates for their renewable electricity production. Certificates are sold to retailers obliged to cover a share of sales by renewable electricity production and represent a source of income additional to the revenue producers earn on selling the electricity itself.<sup>4</sup>

Figure 1 illustrates in a two-country model with electricity trade and transmission investment the effects of introducing a national market for certificates. The right-hand side of the figure depicts country I, which imports electricity from country E on the left-hand side. Production

<sup>&</sup>lt;sup>3</sup> Horn et al. (1994) develop a model of endogenous market integration, but do not consider trade policy. They assume that consumers can purchase in either country, an inappropriate assumption for electricity markets.

<sup>&</sup>lt;sup>4</sup> Certificates and feed-in tariffs are the two most common direct RES-E support systems (Fischer and Preonas, 2010; Schmalensee, 2012). The certificate price is market based, while the feed-in tariff is a regulated price for RES-E production. These two systems have qualitatively similar effects in the present deterministic framework. However, their efficiency properties may differ somewhat, an issue I will return to.

and consumption are on the horizontal axis, and the vertical axis returns the wholesale price of electricity. Electricity is competitively supplied in both countries. Let  $S_i = c'_i$  be the supply cum marginal cost curve of renewable electricity production in country i = I, E. There is also a non-renewable "black" technology. To simplify the graphical exposition, I assume demand for electricity to be constant in both countries. Hence,  $Q_i = D_i - h'_i$  represents the inverse residual demand for renewable electricity in country i, where  $D_i$  is total consumption, and  $h'_i$ is the supply cum marginal cost curve of domestic non-renewable electricity production. The appendix presents a formal analysis of the model under the more general assumption of price elastic aggregate demand. Restricting attention to constant aggregate demand simplifies the graphical exposition without affecting the results in any substantial way.



Figure 1 The international market effects of certificates

Gains from trade render export from country E to I profitable, but bottlenecks in cross-border transmission capacity prevent full price equalization. Hence, electricity is more expensive in import country than the export country even under full utilization of transmission capacity.

Assume first that there are no support systems. The producers in the import country supply  $s_I$  terawatt hours (TWh) renewable electricity at equilibrium price p. Excess demand  $q_I - s_I$  for renewable electricity at wholesale price p is covered by imports  $T_I$ . Producers in the export country supply  $s_E$  TWh renewable electricity at equilibrium price r,  $T_I$  of which is exported, while the remaining  $q_E$  is domestically consumed. Transmission gives rise to a congestion rent  $(p - r)T_I$ . The socially optimal transmission capacity is found at the point at which

marginal transmission cost equals the wholesale price difference between the two countries:  $c'_T(T_I) = p - r$ . This is also the market equilibrium if transmission is competitively supplied.<sup>5</sup>

Let the import country introduce a certificate system with the purpose of increasing renewable electricity production from  $s_I$  to  $q_I$ . The support system for RES-E production depresses the wholesale price of electricity in the import country from p to  $p_I$ . At wholesale price  $p_I$ , a certificate price of  $a_I$  is required to maintain profitability of the targeted  $q_I$  RES-E production. The price reduction in the import country to  $p_I$  implies that congestion rent falls as the price difference between the two markets falls:  $p_I - r . As a result, transmission becomes less profitable and capacity drops from <math>T_I$  to T. Less transmission means less trade, which in turn induces a price drop in the wholesale price from r to  $p_E$  in the export country. The introduction of a certificate system in the import country thus implies less trade and lower wholesale prices in both countries.

Introducing a certificate system in the *export* country lowers the wholesale price in that country from r to  $p_E$ , which in turn accentuates price differences between the two countries:  $p - p_E > p - r$ . Increased congestion rent renders network investment more profitable, resulting in increased trade between the two countries. Increased imports lower the electricity wholesale price of electricity in the importing country from p to  $p_I$ .

**Proposition 1** *A unilateral introduction of certificates for renewable electricity production* (*or increase in the quota obligation*) *in the home country* 

- 1. lowers the electricity wholesale price in both countries;
- 2. lowers the production of non-renewable "black" electricity in both countries;
- 3. lowers (increases) transmission capacity and thereby market integration if the home country is importing (exporting) electricity;
- 4. has ambiguous effects on domestic RES-E production;
- 5. lowers RES-E production abroad if the foreign country does not have any RES-E support system, but increases foreign RES-E production if that country already has a certificate system in place.

<sup>&</sup>lt;sup>5</sup> Most of transmission capacity usually is regulated in restructured electricity markets. If transmission capacity is set at the point at which marginal transmission cost equals the price difference, then all results in this paper trivially hold even under regulation. The main predictions of the model still hold under alternative assumptions about market performance; see Section 5 for a discussion of the robustness of the results.

The negative effects on non-renewable electricity production follow straightforwardly from the decrease in electricity wholesale prices in both countries. As is well known, the effect of certificates on domestic RES-E supply is ambiguous (Amundsen and Mortensen, 2001). Total electricity demand in country *i* falls if certificates push up the retail price  $p_i + f_i a_i$ , where  $p_i$ is the wholesale price and  $a_i$  the certificate price. As RES-E is a constant share  $f_i$  of domestic consumption, the demand reduction may be sufficient to reduce RES-E production. However, domestic RES-E supply increases if the support system is modest, so that  $f_i a_i$  is small or if electricity retail demand is price inelastic, as in Figure 1.

Consider the effect on RES-E supply abroad of introducing a domestic certificate system. Absent any foreign RES-E support, foreign RES-E is determined entirely by the foreign price of electricity. But then foreign RES-E supply must fall because the expansion of the domestic certificate system lowers electricity wholesale prices in both countries. Things are different if the foreign country already has a certificate system in place. The reduction in the wholesale price boosts electricity demand and curbs the supply of black electricity abroad. If RES-E constitutes a fixed share of consumption, then the price fall generates excess demand of RES-E abroad. This leads to an increase in the certificate price and in RES-E production abroad.

Turn next to the effect on producer and consumer surplus of a certificate system in the import country. At the lower wholesale price  $p_I$ , it is only profitable to produce  $g_0$  TWh RES-E in the import country absent any support system. To reach the  $q_I$  target, domestic RES-E production must be subsidized by an amount equal to the sum of the light-coloured area A and the dotted triangle B in Figure 1 to cover the losses to RES-E production in the wholesale market. On the other hand, lower electricity wholesale prices represent a positive terms-oftrade effect on electricity imports by raising consumer surplus by the sum of A and the dark triangle C in the figure. The net effect on producer and consumer surplus in the import country is C-B, which could be positive or negative. The exporting country experiences a negative terms-of-trade effect which lowers consumer and producer surplus in the import country by an amount equal to the darker area D in Figure 1. Total consumer and producer surplus falls by B+D-C in the two countries. In addition, congestion profit falls as a consequence of the reduction in electricity trade between the two countries. If all prices are at their competitive levels, production and transmission are supplied at marginal social cost, and demand represents the marginal social valuation of electricity consumption, this loss in total surplus represents an aggregate welfare loss on the economy. A certificate scheme in this situation distorts not only production and consumption, but also transmission capacity and therefore market integration below the efficient level.

Despite its adverse effects on the economy as a whole, the import country may nonetheless have a unilateral incentive to expand the certificate system. This happens if the positive terms-of-trade-effect dominates the marginal inefficiency of the support system, so that C>B and the loss in transmission profit is not too large. Introducing a certificate system is akin to policy makers in the import country exploiting trade policy to achieve favourable terms-of-trade in the international electricity market. Some trade policy is always profitable.

An electricity exporting country concerned with maximization of domestic surplus would never subsidize the production of green electricity as this would not only distort domestic production but also generate negative terms-of-trade effects. Instead, the exporting country can generate positive terms-of-trade in the electricity market by taxing the production of nonrenewable electricity or by setting a carbon price floor in a market with emissions trading. Total surplus falls also under this alternative support scheme because of distorted production and consumption. A further implication is that market integration falls below its efficient level because of insufficient transmission investment:

**Proposition 2** *Countries participating in a multinational electricity market have incentives to support domestic RES-E production for trade policy reasons even if none of them attach any value to RES-E production itself.* 

- 1. An electricity importing country can raise domestic surplus by a certificate system for renewable electricity production.
- 2. An electricity exporting country can raise domestic surplus by a tax on non-renewable electricity production.
- 3. In an otherwise well-functioning market, domestic RES-E support schemes
  - a. reduce total surplus;
  - b. induce inefficiently low transmission capacity and thereby market integration.

Proposition 2 identifies a trade-off between support mechanisms for renewable electricity and market integration under decentralized policy making. Certificates and taxes on non-renewable electricity production are only examples of the policies countries might introduce for trade policy reasons. The general purpose of direct and indirect RES-E policies is for the

import (export) country to lower (raise) the import (export) electricity wholesale price. Any RES-E policy which serves this purpose will do.

#### 3. Market external effects of renewable electricity production

The analysis has so far built upon the assumption that all costs and benefits of electricity production and transmission are captured by consumer and producer surplus in the electricity wholesale market. RES-E support schemes in this case reduce aggregate welfare in an otherwise well-functioning electricity market. Notwithstanding these market distortions, RES-E mechanisms are justified if there are welfare benefits to renewable electricity production not fully internalized in market prices. The most obvious externality would be positive climate effects of RES-E production. But even with an emission trading system in place aimed at internalizing climate effects of electricity production, policy makers sometimes perceive of additional benefits to RES-E neither captured by electricity prices nor by emission prices. One of them is spill-over effects from renewable technologies (Fischer and Newell, 2008).

I add an aggregate benefit  $B(g_E, g_I)$  of RES-E to the model in the previous section, which is not internalized by market participants through electricity wholesale prices alone. Let  $(g_E^*, g_I^*)$ be the socially optimal production of RES-E in the two countries. The positive renewables externality means that the marginal social cost of RES-E,  $S_i^* = c_i' - B_{g_i}(\cdot, g_j^*)$ , is lower than the marginal production cost  $S_i = c_i'$ . The competitive solution thus delivers insufficient RES-E supply. The socially optimal transmission capacity is found where the marginal social cost difference of renewable electricity production equals the marginal cost of transmission:  $S_I^*(g_I^*, g_E^*) - S_E^*(g_E^*, g_I^*) = c_T'(T^*)$ . Transmission could be over- or undersupplied at competitive equilibrium because import and export prices are distorted in the same direction.

Figure 2 illustrates a socially optimal support system. A production subsidy of  $a_i^* = B_{g_i}(g_i^*, g_j^*)$  in both countries financed by lump-sum transfers aligns production incentives.<sup>6</sup> It is not necessary to correct transmission investment because the marginal social cost of RES-E here is included in the electricity wholesale price:  $p_i^* = c_i'(g_i^*) - B_{g_i}(g_i^*, g_j^*)$ . But sometimes it is necessary to correct also transmission at the social optimum because investments based upon congestion rent alone are distorted. An equivalent solution to a RES-E subsidy is a tax

<sup>&</sup>lt;sup>6</sup> Certificates cannot implement the social optimum unless demand is completely inelastic because they drive a wedge between consumers' marginal utility of consumption and marginal production cost; see the appendix for a characterization of the social optimum.

on non-renewable production,  $\tau_i^* = B_{g_i}(g_i^*, g_j^*)$ , redistributed in a lump-sum manner. With taxes, the wholesale price difference  $p_l^* - p_E^* = c_l'(g_l^*) - c_E'(g_E^*)$  does not fully capture differences in the marginal social cost of renewable electricity between countries. Instead, transmission owners should receive a congestion price corrected for taxes:  $p_l^* - p_E^* + \tau_E^* - \tau_l^*$ .





The next question is whether decentralized policy making can implement the social optimum. In general, the answer is no. First, increased RES-E production at home could have external effects abroad which the domestic policy maker fails to internalize. If  $B_i(g_i, g_j)$  is the market external effect of RES-E in country *i*, then cross-border externalities arise if  $\partial B_i/\partial g_j \neq 0$ . But decentralized decision making is problematic even without cross-border externalities, i.e.  $B_i(g_i, g_j) = B_i(g_i)$ . For trade policy reasons, the import (export) country has an incentive to deviate from the social optimum by increasing (reducing) renewable support. Consequently, market integration falls below the social optimum.<sup>7</sup>

Supranational intervention is required to improve total welfare. Ogawa and Wildasin (2009) show that it could be enough to decide an appropriate renewable target for the economy as a whole and to decentralize policy making to the individual countries, if aggregate renewables are what matter to the economy:  $B(g_E, g_I) = B(g_E + g_I)$ . While policy makers may select polices that maximize domestic welfare, investments flow between countries in a manner which equates the marginal social cost of RES-E across countries, thereby ensuring efficiency at equilibrium. But this result relies on the assumption that policy makers treat prices as given

<sup>&</sup>lt;sup>7</sup> Tangerås (2013) states and proves this result in the context of direct subsidies to RES-E production financed by lump-sum transfers.

in the international market. If policy makers instead take into account the effects of domestic policies on electricity prices, then decentralized decision making comes at a social cost.

**Proposition 3** If RES-E targets are fixed at the social optimum  $(g_E^*, g_I^*)$ , but national policy makers are free to choose in a decentralized manner the policies with which to reach these targets, then resource allocation still is inefficient.

- 1. An electricity importing (exporting) country maximizing domestic welfare selects a combination of instruments which lowers (raises) electricity wholesale prices below (above) the efficient level.
- 2. Domestic policies distort transmission investment and thereby market integration below the social optimum.

Proposition 3 shows that increased market integration may stand in conflict with other energy policy goals of the EU, not least owing to the decentralized manner in which some of these goals are attained. National policy makers have access to a host of policy instruments for promoting RES-E such as certificates, feed-in tariffs and direct investment support. Taxes on non-renewable electricity production and consumption are other standard tools in the policy maker's toolbox. This plethora of instruments leaves ample room for national policy makers to pursue objectives unrelated to the environment, to renewable electricity production or to energy efficiency. For example, an electricity importing country can suppress electricity prices and improve its terms-of-trade by taxing electricity consumption. A corresponding increase in subsidies to RES-E production allows the country to meet its national renewables target even at lower electricity prices. An electricity exporting country can raise the electricity price and thus improve its terms-of-trade by taxing non-renewable electricity production. The policy maker can neutralize any incentive to overinvest in renewable electricity by lowering renewables subsidies. One such instrument is a feed-in tariff with a cap on total revenues which fully offsets profit increases resulting from taxes on non-renewable electricity.

Trade policy disguised as renewable policy distorts market integration below the social optimum because inefficiently high (low) export (import) prices reduce congestion rent, hence the profitabily of transmission investment. One way to offset the negative consequences of domestic policies would be to strengthen market integration by subsidizing transmission investment. Consider a transfer mT on top of congestion rent, financed by a lump-sum tax on electricity consumers in the two countries:

**Proposition 4** If RES-E targets are fixed at the social optimum  $(g_E^*, g_I^*)$ , but national policy makers are free to choose in a decentralized manner the policies with which to reach these targets, then there exists a transmission subsidy m > 0 which increases total surplus.<sup>8</sup>

Transmission regulation limits the distortions to transmission capacity, but does not eliminate the scope for trade policy. Policy makers still can manipulate international electricity prices to their benefit by domestic policies.<sup>9</sup> Instead, it is necessary to harmonize national policies and reduce the number of instruments available to national policy makers. In the model, setting the national renewable targets at their socially optimal level and requiring the exclusive use of renewable subsidies financed by lump-sum transfers uniquely implements the social optimum if the market is otherwise competitive.<sup>10</sup> But this centralized policy is demanding in terms of the information needed to implement the solution. It requires that the centralized planner knows, not only the socially optimal amount of renewables, but also the correct distribution of costs and benefits of renewables throughout the economy. More plausible is the assumption that the central planner is not fully informed about all relevant aspects of the economy. Under asymmetric information, integrated support schemes can increase efficiency. The next section considers one such scheme, an integrated certificate market.

#### 4. An integrated certificate market

The joint Swedish and Norwegian certificate market opened in 2012 and was the world's first multinational certificate market. In this market a consumer fulfills her quota obligation either by purchasing Norwegian or Swedish certificates. Perfect substitutability between certificates and zero trade costs imply a uniform certificate price in the two countries.

Figure 3 illustrates the effect of certificate market integration, starting from a situation with two autarkic certificate markets. Initially, country *I* produces  $g_I$  TWh renewable electricity at wholesale price *p* and certificate price  $a_I$ . Excess demand at price *p* is covered by *T* TWh imports from country *E*, which produces  $g_E$  TWh renewable electricity at wholesale price *r* and certificate price  $a_E$ . Transmission capacity is at the competitive level:  $p - r = c'_T(T)$ .

<sup>&</sup>lt;sup>8</sup> The Renewables Grid Initiative argues in a note to the DG budget that public cofunding at the EU level would facilitate investment in cross-border capacity and thereby increase market integration (<u>http://renewables-grid.eu/documents/position-papers.html</u>), June 10, 2013). Proposition 4 shows that cofounding could be efficient. <sup>9</sup> In the proof of Proposition 4, I show that domestic policy makers distort prices for any  $m \ge 0$ .

<sup>&</sup>lt;sup>10</sup> See Tangerås (2013) for the proof of this statement.

Figure 3 Certificate market integration



Assume that the two countries integrate their certificate markets. Certificate trade drives down the certificate price in country I and raises the certificate price in country E until the price is equalized in both countries and the certificate market clears at a. Under the assumption of price inelastic electricity demand (this is for expositional purposes only), the relative price change of certificates drives up renewable electricity production by M in country E with a corresponding reduction in country I. As a consequence, the wholesale price of electricity falls from r to  $p_E$  in the export country and increases from p to  $p_I$  in the import country. The increased price difference raises congestion rent which triggers network investment. Exports increase to  $T_I$  (not indicated in the figure), where  $p_I - p_E = c'_T(T_I)$ .

If, on the other hand, the certificate price initially is comparatively lower in the importing country,  $a_I < a_E$ , then certificate market integration increases (lowers) renewable electricity production in the import (export) country. This reallocation of renewable production from the exporting country to the importing country drives down price differences between the two markets, which in turn reduce trade and market integration:

**Proposition 5** If the electricity exporting (importing) country possesses a comparative advantage in the production of renewable electricity, then certificate market integration increases (lowers) transmission investment and thereby electricity market integration. Certificate market integration raises total surplus in the electricity wholesale market.

Certificate trade implies that the production inefficiency associated with electricity certificates falls in country I by the scratched area in the right-hand side of Figure 3, but increases in country E by the scratched area on the left-hand side. The net effect is positive. But contrary

to common belief, e.g. Söderholm (2008) and Schmalensee (2012), efficiency of an integrated certificate market does *not* imply equalization of renewable marginal production costs across the market. Hence, one could not draw the conclusion that integrated certificate markets were inefficient based simply upon an observation that marginal costs of renewable electricity production differ across the market. In Figure 3, renewable electricity is produced at marginal cost  $p_I + a$  in the import country at the social optimum, which is higher than the marginal cost  $p_E + a$  of renewable electricity in the export country. Under certificate market autarky, the certificate price  $a_I$  measures the marginal deadweight loss in the electricity market associated with renewable electricity support in the import country because  $a_I$  is the difference between the marginal production cost  $p + a_I$  of green electricity and the marginal production cost p of black electricity. Similarly,  $a_E$  represents the marginal deadweight loss of renewable electricity support in the export country. Certificate market integration increases efficiency by equating the marginal deadweight loss of renewable electricity across markets:  $a_I = a_E = a$ . Marginal production costs are equalized if and only if wholesale prices are the same in all markets. But transmission capacity is costly, so bottlenecks generally prevent full equalization of electricity wholesale prices at the social optimum.

Certificate market integration induces a reallocation of renewable electricity investment to the country with the lowest certificate price in autarky. In Figure 3, RES-E production increases by M in country E and falls by the same amount in country I under integration. Aggregate RES-E production may generally decrease with certificate market integration and render it more difficult to attain an aggregate production target  $g_E + g_I$ . If the distribution of RES-E investments matters, i.e.  $B_{g_I}(g_I^*, g_E^*) \neq B_{g_E}(g_E^*, g_I^*)$ , then differentiated certificate prices are required at social optimum. Full integration of certificate markets is suboptimal in that case. Certificate market integration thus may entail a trade-off between higher efficiency in the electricity wholesale market and the achievement of aggregate and national RES-E targets.

#### 5. Discussion

This paper investigates the interplay between decentralized support policies for renewable electricity production, RES-E, and market integration in a multinational electricity market and derives a number of testable predictions. In particular, electricity importing countries have incentives to implement policies which serve to lower the import price of electricity, such as subsidies to RES-E or consumption taxes. Electricity exporting countries benefit from policies which raise export prices, such as taxes on non-renewable electricity production. A driving

force behind the EU Renewables Directive was a concern with resource adequacy. At an aggregate level, model predictions are consistent with EU promoting renewable energy to reduce import dependence of natural gas from Russia.

The analysis rests upon the assumption that generation and transmission are competitively supplied. Most electricity markets are concentrated and therefore susceptible to the exercise of market power; see Wolfram (1999) or Borenstein et al. (2002) for classical treaties. Domestic transmission networks often are owned by one or several transmission network operators (TSOs) subject to regulation. But main predictions of the model appear robust to changes in market performance. For example, subsidies tend to increase RES-E investment and thereby reduce electricity prices even under imperfect competition. Lower congestion rent would have a negative effect on transmission investment even under regulation.<sup>11</sup> A pro-competitive effect of market integration arises under imperfect competition because transmission bottlenecks limit competition (Holmberg and Philpott, 2012). This additional externality suggests that distortions of market integration associated with domestic RES-E policies are equally and perhaps even more substantial under imperfect product market competition.

The empirical predictions are derived in a two-country model with unidirectional electricity trade. In reality, electricity often flows in both directions over the course of a year to balance local demand and supply fluctuations. Countries usually have more than one trading partner, exporting electricity to one country while importing it from another. The overall incentive to subsidize renewable production or tax non-renewable production depends on net trade flows and the sensitivity of electricity prices to domestic policy changes. If, for example, net traded volume is zero, but imports to the home country are less price sensitive than exports, then the home country still benefits from subsidies to RES-E. To test the model predictions one would first have to construct an appropriate electricity trade index.

The model relies upon the assumption that decentralized policies maximize domestic welfare: policy makers attach equal weight to consumer and producer surplus within the country. The electricity intensive industry and other consumer groups usually lobby for lower electricity prices. Producers benefit from higher electricity prices, and one would not be surprised to see power companies with a large portfolio of renewable production lobbying in favour of taxes

<sup>&</sup>lt;sup>11</sup>As an illustrative case in point the Swedish TSO, Svenska Kraftnät, is under governmental instruction to invest all its congestion rent in transmission. While inducing excessive investment, this policy also has the consequence that reductions in congestion rent reduces transmission investment.

on dirty technologies. Energy policy depends also on the lobbying efforts of these and other interest groups. Jenner et al. (2012) analyze the political determinants of RES-E support in the EU. They find a long presence of a chapter of the International Solar Energy Association to increase the likelihood of RES-E support in that country. The authors do not consider the link between trade flows an RES-E policy. In light of the results of the present analysis, this might prove a fruitful venue for future empirical research on the determinants of RES-E policy.

### Appendix

This Appendix formally analyzes the model which the analysis in the main text rests upon. There are two countries, the export country, indexed by *E*, and the import country, indexed by I. The representative consumer in country i = E, I purchases q TWh electricity to maximize quasi-linear utility  $u_i(q) - (p_i + f_i a_i)q$ , where  $p_i$  is the electricity wholesale price,  $f_i$  the quota obligation and  $a_i$  the certificate price in country *i*. The utility function  $u_i(q)$  is twice continuously differentiable, strictly increasing and strictly concave, with  $\lim_{q\to 0} u_i'(q) = \infty$ . Indirect utility is  $v_i(p_i + f_i a_i) = \max_{q \ge 0} [u_i(q) - (p_i + f_i a_i)q]$ . Define electricity demand in country *i* by  $q_i = D_i(p_i + f_i a_i)$ . There are two types of electricity production in country *i*, renewable or "green" electricity in amount  $g_i$  and non-renewable or "black" electricity in amount  $b_i$ , with respective cost functions  $c_i(g_i)$  and  $h_i(b_i)$ . Both cost functions are twice continuously differentiable, strictly increasing and strictly convex with  $\lim_{g\to 0} c'_i(g) = 0$  and  $\lim_{b\to 0} h'_i(b) = 0$ . The profit of the two types of production are  $(p_i + a_i)g_i - c_i(g_i)$  and  $p_i b_i - h_i(b_i)$ , respectively. Electricity is exported from E to I in amount T, where T is the capacity of the cross-border interconnection between E and I. Congestion profit equals  $(p_I - p_E)T - c_T(T)$ , where  $c_T(T)$  is the strictly increasing, twice continuously differentiable and strictly convex cost of providing transmission, with  $\lim_{T\to 0} c'_T(T) = 0$ .

Assume that electricity and transmission are both competitively supplied. The set of firstorder conditions (i = I, E):

$$p_i + a_i = c'_i(g_i), p_i = h'_i(b_i), p_I - p_E = c'_T(T)$$
(1)

plus the set of market-clearing conditions

$$g_i = f_i D_i (p_i + f_i a_i), b_i = (1 - f_i) D_i (p_i + f_i a_i) + (-1)^{\frac{i - E}{I - E}} T$$
(2)

.

define the unique interior equilibrium under the assumption of no certificate trade between the two countries.

#### **Proof of Proposition 1**

By total differentiation of the equilibrium conditions above  $(i \neq j = E, I)$ :

$$\begin{aligned} \frac{\partial p_i}{\partial f_i} &= -\Omega h_i'' \left( K_j + \left( 1 - f_j^2 c_j'' D_j' \right) \frac{h_j''}{c_T''} \right) [q_i (1 - f_i c_i'' D_i') - a_i (1 - f_i) D_i'] < 0, \\ \frac{\partial p_i}{\partial f_j} &= -\Omega \frac{h_i'' h_E''}{c_T''} (1 - f_i^2 c_i'' D_i') [q_j (1 - f_j c_j'' D_j') - a_j (1 - f_j) D_j'] < 0, \end{aligned}$$

where

$$K_E = 1 - (f_E^2 c_E'' + (1 - f_E)^2 h_E'') D_E' > 1,$$

 $K_I$  is similarly defined, and

$$\Omega^{-1} = K_I K_E + \frac{h_I''}{c_T''} (1 - f_I^2 c_I'' D_I') K_E + \frac{h_E''}{c_T''} (1 - f_E^2 c_E'' D_E') K_I > 1.$$

The comparative statics above reveal that the electricity wholesale price at home is strictly decreasing in the quota obligation at home and abroad.

Evaluating the effects of the support system on non-renewable electricity is straightforward. Bearing in mind the first-order condition  $p_i = h'_i(b_i)$  and the price effects  $\partial p_i / \partial f_i < 0$  and  $\partial p_i / \partial f_E < 0$ :

$$\frac{\partial b_i}{\partial f_I} = \frac{1}{h_i''} \frac{\partial p_i}{\partial f_I} < 0, \frac{\partial b_i}{\partial f_E} = \frac{1}{h_i''} \frac{\partial p_i}{\partial f_E} < 0.$$

Hence, the supply of non-renewable electricity is decreasing in the quota obligations independently of whether the increase is at home or abroad.

Consider next the real effects of the certificate system on transmission capacity. Using  $p_I - p_E = c'_T(T)$  and the price effects above, I obtain after simplifications ( $i \neq j = I, E$ ):

$$\frac{\partial T}{\partial f_i} = \frac{1}{c_T^{\prime\prime}} \left( \frac{\partial p_I}{\partial f_i} - \frac{\partial p_E}{\partial f_i} \right) = (-1)^{\frac{i-E}{I-E}} \Omega \frac{h_i^{\prime\prime}}{c_T^{\prime\prime}} [q_i(1 - f_i c_i^{\prime\prime} D_i^{\prime}) - a_i(1 - f_i) D_i^{\prime}] K_j.$$

As is readily apparent, transmission capacity and trade are lower (higher) if the quota obligation in the importing (exporting) country is higher  $(\partial T/\partial f_I < 0 \text{ and } \partial T/\partial f_E > 0)$ .

Consider next the effect on RES-E production. It is useful to study the effect on the certificate price. The effect on the domestic certificate price of an increase in the own quota obligation

$$\begin{aligned} \frac{\partial a_i}{\partial f_i} &= \Omega h_i'' [K_j + (1 - f_j^2 c_j'' D_j') \frac{h_j''}{c_T''}] [q_i (1 - c_i'' D_i') - a_i (1 - f_i) D_i'] \\ &+ \Omega c_i'' [(1 + \frac{h_i''}{c_T''}) K_j + (1 - f_j^2 c_j'' D_j') \frac{h_j''}{c_T''}] [q_i + a_i f_i D_i'] \end{aligned}$$

is ambiguous in general, but positive if electricity demand is inelastic or the support system is small enough ( $f_i a_i$  is small):

$$-\frac{(p_i+a_if_i)D'_i}{q_i} \le \frac{p_i+a_if_i}{a_if_i}.$$

However, the domestic certificate price is strictly increasing in the quota obligation abroad:

$$\frac{\partial a_i}{\partial f_j} = \Omega \frac{h_i'' h_E''}{c_T''} (1 - f_i c_i'' D_i') [q_j (1 - f_j c_j'' D_j') - a_j (1 - f_j) D_j'] > 0.$$

Invoking the first-order condition  $p_i + a_i = c'_i(g_i)$ , I obtain

$$\begin{aligned} \frac{\partial g_i}{\partial f_i} &= \frac{1}{c_i''} \left( \frac{\partial p_i}{\partial f_i} + \frac{\partial a_i}{\partial f_i} \right) = -\Omega h_i'' (1 - f_i) [K_j + (1 - f_j^2 c_j'' D_j') \frac{h_j''}{c_T''}] q_i D_i' \\ &+ \Omega [(1 + \frac{h_i''}{c_T''}) K_j + (1 - f_j^2 c_j'' D_j') \frac{h_j''}{c_T''}] [q_i + a_i f_i D_i'], \end{aligned}$$

which is ambiguous, but strictly positive if, for example, electricity demand is inelastic or the support system is small enough.

I need to consider separately the case of RES-E support systems from the case without RES-E support when analyzing the predicted effects on renewable electricity production abroad. If there exists a certificate system abroad, then

$$\frac{\partial g_i}{\partial f_j} = f_i D'_i \frac{\partial (p_i + f_i a_i)}{\partial f_j} = -f_i D'_i \Omega \frac{h''_I h''_E}{c''_T} (1 - f_i) \left[ q_j \left( 1 - f_j c''_j D'_j \right) - a_j \left( 1 - f_j \right) D'_j \right] > 0,$$

by the market clearing condition  $g_i = f_i D_i (p_i + f_i a_i)$ . Absent any RES-E support abroad, equilibrium renewable production is characterized by the first-order condition  $p_i = c'_i(g_i)$ . By necessity,  $\partial g_i / \partial f_j < 0$  because  $\partial p_i / \partial f_j < 0$ . Note finally that the domestic retail price is ambiguous to changes in the own quota obligation:

$$\frac{\partial(p_i + f_i a_i)}{\partial f_i} = \frac{\partial p_i}{\partial f_i} + f_i \frac{\partial a_i}{\partial f_i} + a_i$$
  
=  $\Omega \frac{h_i'' h_i''}{c_T''} K_j (1 - f_i) q_i + \Omega \left[ (1 + \frac{h_i''}{c_T''}) K_j + (1 - f_j^2 c_j'' D_j') \frac{h_j''}{c_T''} \right] [a_i + q_i (f_i c_i'' - (1 - f_i) h_i'')].$ 

But as is also well known, the retail price is increasing in the own quota obligation if either the certificate price  $a_i$  is high, the quota obligation  $f_i$  is large, the supply of renewable electricity is inelastic ( $c''_i$  is large) or the supply of non-renewable electricity is elastic ( $h''_i$  is small), i.e.  $a_i + q_i(f_ic''_i - (1 - f_i)h''_i) \ge 0$ .

#### **Proof of Proposition 2**

Assume that all domestic electricity production is owned by domestic firms and that country i = I, E earns a share  $\alpha_i$  of congestion profit. Surplus in country *i* is the sum of domestic consumer surplus, domestic firm profit and the country's share of congestion profit:

 $w_i = v_i(p_i + f_i a_i) + (p_i + a_i)g_i - c_i(g_i) + p_i b_i - h_i(b_i) + \alpha_i[(p_I - p_E)T - c_T(T)],$ where I for notational simplicity have subsumed the fact that prices, production and transmission capacity all depend on  $(f_I, f_E)$  at competitive equilibrium. By repeated use of the envelope theorem on consumer surplus, producer and transmission profits, and the market clearing conditions  $g_i = f_i q_i, b_I + T = (1 - f_I)q_I$  and  $b_E - T = (1 - f_E)q_E$ :

$$\frac{\partial w_I}{\partial f_i} = -(\alpha_E \frac{\partial p_I}{\partial f_i} + \alpha_I \frac{\partial p_E}{\partial f_i})T - X_i a_I q_I, \\ \frac{\partial w_E}{\partial f_i} = (\alpha_E \frac{\partial p_I}{\partial f_i} + \alpha_I \frac{\partial p_E}{\partial f_i})T - (1 - X_i)a_E q_E,$$

where  $X_I = 1$  and  $X_E = 0$ . Summing up yields

$$\frac{\partial w_I}{\partial f_i} + \frac{\partial w_E}{\partial f_i} = -X_i a_I q_I - (1 - X_i) a_E q_E < 0$$

Total surplus falls with an increase in the quota obligation in any country. However, the effects are asymmetrically distributed.

Surplus in the import country unambiguously increases with increases in the quota obligations abroad  $(\partial w_I / \partial f_E > 0)$ , but may increase or fall as the quota obligation at home increases  $(\partial w_I / \partial f_I \ge 0)$ . Define  $f_{I0} \ge 0$  as the share of certified electricity that would prevail in equilibrium in country *I* absent a renewable support scheme in that country, i.e.  $a_I(f_{I0}, f_E) = 0$ . Note that:

$$\left|\frac{\partial w_I}{\partial f_I}\right|_{f_I = f_{I0}} = -(\alpha_E \frac{\partial p_I}{\partial f_I} + \alpha_I \frac{\partial p_E}{\partial f_I})T > 0,$$

so the import country has an incentive to introduce a (small) certificate system even if the policy maker is only concerned with domestic surplus and places no intrinsic value on renewable electricity.

Surplus in the export country unambiguously falls with increases in the quota obligations at home and abroad  $(\partial w_E / \partial f_E < 0 \text{ and } \partial w_I / \partial f_I < 0)$ . Therefore, a policy maker in the export country aiming to increase domestic surplus would never introduce certificates. To the contrary, national surplus would increase by a RES-E support scheme implemented through a *tax* on non-renewable electricity; see Tangerås (2013).

Subsidies to renewable electricity production in the import country and taxes on nonrenewable electricity production in the export country reduce the difference  $p_I - p_E$  below what maximizes total surplus. As transmission capacity (market integration) is monotonically increasing in  $p_I - p_E$ , the unilateral pursuit of domestically optimal renewable electricity support schemes implies inefficiently low market integration.

#### Implementation of the social optimum

The benevolent social planner maximizes

$$B(g_{I}, g_{E}) + \sum_{i=I,E} (u_{i}(q_{i}) - c_{i}(g_{i}) - h_{i}(b_{i})) - c_{T}(T)$$

over  $(q_I, g_I, b_I)$ ,  $(q_E, g_E, b_E)$  and *T* subject to the market clearing constraints  $q_I \leq g_I + b_I + T$  and  $q_E \leq g_E + b_E - T$ . The benefit *B* of renewable electricity production is strictly increasing in both arguments, twice continuously differentiable and strictly concave. Let  $\lambda_i$  be the Lagrangian multiplier associated with the market clearing constraint in *i*. The first-order conditions (i = I, E):

$$B_{g_i}(g_I^*, g_E^*) + \lambda_i^* = c_i'(g_i^*), \ \lambda_i^* = h_i'(b_i^*), \ u_i'(q_i^*) = \lambda_i^*, \ \lambda_I^* - \lambda_E^* = c_T'(T^*)$$

and complementary slackness conditions

$$\lambda_{I}^{*}(g_{I}^{*}+b_{I}^{*}+T^{*}-q_{I}^{*})=0$$
,  $\lambda_{E}^{*}(g_{E}^{*}+b_{E}^{*}-T^{*}-q_{E}^{*})=0$ ,  $\lambda_{i}^{*}\geq0$ 

jointly characterize the unique social optimum.

The social optimum equates the marginal social cost of production across technologies in both countries:  $\lambda_i^* = c_i'(g_i^*) - B_{g_i}(g_i^*, g_E^*) = h_i'(b_i^*)$ . Optimal transmission capacity is at the point at which marginal transmission cost equals the difference in marginal social production cost of renewable electricity production between the import and the export country:  $c_T'(T^*) = c_i'(g_i^*) - B_{g_i}(g_i^*, g_E^*) - c_E'(g_E^*) + B_{g_E}(g_i^*, g_E^*)$ .

The social optimum can be implemented as a competitive equilibrium with subsidies to renewable production financed by lump-sum taxation of electricity consumers. A wholesale price of  $p_i^* = \lambda_i^*$ , a renewable production subsidy of  $a_i^* = B_{g_i}(g_I^*, g_E^*)$  and the socially optimal allocations solve the first-order conditions for production and transmission and clear the electricity markets in both countries. With renewable production subsidies alone, competitive transmission supply is socially optimal:  $c'_T(T^*) = p_I^* - p_E^*$ . Given subsidies  $a_I^*$  and  $a_E^*$ , firms produce the socially optimal shares of renewable production

$$f_I^* = rac{g_I^*}{g_I^* + b_I^* + T^*}, \ f_E^* = rac{g_E^*}{g_E^* + b_E^* - T^*}.$$

Lump-sum transfers from consumers in total amount  $a_I^* g_I^* + a_E^* g_E^*$  entail no welfare costs under quasi-linear preferences. However, certificates cannot implement the social optimum because they distort marginal retail prices. At the social optimum,  $u'_i(q_i^*) = h'_i(b_i^*)$ . Instead,  $u'_i(q_i) = p_i + a_i f_i \ge p_i = h'_i(b_i)$  in a competitive electricity market with certificates, with equality if and only if  $a_i f_i = 0$ . Hence, certificates are efficient only if  $a_I f_I = a_E f_E = 0$ . But then certificates cannot cover the losses to RES-E production.

An equivalent solution to subsidizing renewables is to tax non-renewable production by  $\tau_i^* = B_{g_i}(g_I^*, g_E^*)$ , let renewable production receive the wholesale price  $p_i^* = \lambda_i^* + B_{g_i}(g_I^*, g_E^*)$  and redistribute tax revenue  $\tau_I^* g_I^* + \tau_E^* b_E^*$  to consumers in a lump-sum fashion. Under this alternative support mechanism, consumers pay the net wholesale price,  $p_i^* - \tau_i^*$ , and the owners of transmission receive a congestion price corrected for taxes:  $p_I^* - p_E^* + \tau_E^* - \tau_I^*$ .

#### **Proof of Proposition 3**

Let  $B_I(g_I, g_E) + B_E(g_E, g_I) = B(g_I, g_E)$ . If, for example, welfare in country *i* equals

 $B_i(g_i^*, g_j^*) + u_i(q_i^*) - c_i(g_i^*) - h_i(b_i^*) + \lambda_i^*(g_i^* + b_i^* - q_i^*) + \alpha_i((\lambda_i^* - \lambda_E^*)T^* - c_T(T^*))$ at the social optimum, where  $\lambda_i^* = h_i'(b_i^*)$ , then the policy maker of that country is indifferent between all national policies which implement the social optimum. The reason is that domestic welfare then depends entirely on the allocations  $(g_i^*, b_i^*, q_i^*)$ ,  $(g_E^*, b_E^*, q_E^*)$  and  $T^*$ . I only need to show that national policy makers have a unilateral incentive to deviate from some socially optimal policy to establish incentive incompatibility of decentralized decision making in this case. Let the default policy be the renewable production subsidy  $a_i^* = B_{g_i}(g_i^*, g_j^*)$  with wholesale price  $p_i^* = \lambda_i^*$  financed by the lump-sum transfer  $a_i^* g_i^*$ .

Fix renewables production at  $(g_I^*, g_E^*)$ . Assume that country *E* applies a combination of a nonrenewables production tax  $\tau_E \ge 0$  and renewables production subsidy  $a_E$  to attain its renewable target  $g_E^*$ . Country *I* uses a mix of a consumption tax  $\phi_I \ge 0$  and renewables production subsidy  $a_I$  to reach its target  $g_I^*$ . Both countries balance their budgets by lumpsum net transfers to electricity consumers. Assume that transmission investment is subsidized at the central level by *mT*, the cost of which is redistributed across countries in a lump-sum fashion according to the distribution of transmission ownership shares. To simplify analysis, assume that domestic policies and *m* are set simultaneously. Define electricity demand  $q_I = D_I(p_I + \phi_I)$  and  $q_E = D_E(p_E)$ . The first-order conditions

$$p_I = h'_I(b_I), p_E - \tau_E = h'_E(b_E), m + p_I - p_E = c'_T(T)$$
 (3)

and market-clearing conditions

$$D_I(p_I + \phi_I) = g_I^* + b_I + T, D_E(p_E) = g_E^* + b_E - T$$
(4)

uniquely define equilibrium wholesale prices  $(p_I, p_E)$ , non-renewable production  $(b_I, b_E)$  and transmission *T* as functions of  $(\phi_I, \tau_E, m)$ . Given the equilibrium price  $p_i$ , the policy maker in country *i* sets the production subsidy residually to implement the country's renewables target:  $a_i = c'_i(g^*_i) - p_i$ . By uniqueness of the competitive equilibrium and the social optimum, these policies implement the social optimum if and only if  $\phi_I = \tau_E = m = 0$ .

By total differentiation of the equilibrium conditions:

$$dp_{I} = \Upsilon(\frac{1}{h_{E}''} + \frac{1}{c_{T}''} - D_{E}')D_{I}'d\phi_{I} + \frac{\Upsilon}{h_{E}''c_{T}''}d\tau_{E},$$
$$dp_{E} = \frac{\Upsilon D_{I}'}{c_{T}''}d\phi_{I} + \frac{\Upsilon}{h_{E}''}(\frac{1}{h_{I}''} + \frac{1}{c_{T}''} - D_{I}')d\tau_{E},$$

where

$$\Upsilon^{-1} = (\frac{1}{h_I''} - D_I')(\frac{1}{h_E''} - D_E') + \frac{1}{c_T''}(\frac{1}{h_I''} - D_I' + \frac{1}{h_E''} - D_E') > 0.$$

Thus, electricity wholesale prices in both countries (i = I, E) are decreasing in the consumption tax  $(\delta p_i / \delta \phi_I < 0)$  and increasing in the non-renewables production tax  $(\delta p_i / \delta \tau_E > 0)$ . The domestic effect is stronger than the foreign effect, so the price difference is falling in both policies:

$$dT = \frac{1}{c_T''}(dp_I - dp_E) = \frac{\Upsilon}{c_T''}(\frac{1}{h_E''} - D_E')D_I'd\phi_I - \frac{\Upsilon}{h_E''c_T''}(\frac{1}{h_I''} - D_I')d\tau_E.$$

Thus, transmission capacity is falling in both policies:  $\delta T/\delta \phi_I < 0$  and  $\delta T/\delta \tau_E < 0$ . Finally,

$$db_{I} = \frac{1}{h_{I}''} dp_{I} = \frac{\Upsilon}{h_{I}''} (\frac{1}{h_{E}''} + \frac{1}{c_{T}''} - D_{E}') D_{I}' d\phi_{I} + \frac{\Upsilon}{h_{I}'' h_{E}'' c_{T}''} d\tau_{E},$$
  
$$db_{E} = \frac{1}{h_{E}''} (dp_{E} - d\tau_{E}) = \frac{\Upsilon D_{I}'}{h_{E}'' c_{T}''} d\phi_{I} - \frac{\Upsilon}{h_{E}''} [\frac{1}{c_{T}''} (\frac{1}{h_{I}''} - D_{I}' - D_{E}') - h_{E}'' (\frac{1}{h_{I}''} - D_{I}') D_{E}'] d\tau_{E},$$

and

$$dq_{I} = D'_{I}(dp_{I} + d\phi_{I}) = \Upsilon[(\frac{1}{h''_{I}} + \frac{1}{c''_{T}})(\frac{1}{h''_{E}} - D'_{E}) + \frac{1}{c''_{T}h''_{I}}]D'_{I}d\phi_{I} + \frac{\Upsilon D'_{I}}{h''_{E}c''_{T}}d\tau_{E},$$
  
$$dq_{E} = \frac{\Upsilon D'_{E}D'_{I}}{c''_{T}}d\phi_{I} + \frac{\Upsilon}{h''_{E}}(\frac{1}{h''_{I}} + \frac{1}{c''_{T}} - D'_{I})D'_{E}d\tau_{E}$$

imply that a higher consumption tax in country *I* leads to lower non-renewable production in both countries  $(\delta b_i / \delta \phi_I < 0)$  and lower (higher) consumption in the import (export) country:  $\delta q_I / \delta \phi_I < 0$  ( $\delta q_E / \delta \phi_I > 0$ ). Consumption in both countries fall with increases in the nonrenewables production tax in country ( $\delta q_i / \delta \tau_E < 0$ ), while "black" production increases (falls) in the import (export) country:  $\delta b_I / \delta \tau_E > 0$  ( $\delta b_E / \delta \tau_E < 0$ ).

The marginal effect on welfare

$$B_{I}(g_{I}^{*},g_{E}^{*}) + u_{I}(q_{I}) - p_{I}T - c_{I}(g_{I}^{*}) - h_{I}(b_{I}) + \alpha_{I}((p_{I} - p_{E})T - c_{T}(T))$$

in country I of increasing the consumption tax is given by

$$\phi_I \frac{\partial q_I}{\partial \phi_I} - (\alpha_E \frac{\partial p_I}{\partial \phi_I} + \alpha_I \frac{\partial p_E}{\partial \phi_I})T - \alpha_I m \frac{\partial T}{\partial \phi_I}$$

after simplifying. It is ambiguous in general by  $\delta q_I / \delta \phi_I < 0$ ,  $\delta p_i / \delta \phi_I < 0$  and  $\delta T / \delta \phi_I < 0$ , but strictly positive if  $m \ge 0$  and  $\phi_I$  is small, but positive. Analogously, the marginal effect

$$\tau_E \frac{\partial b_E}{\partial \tau_E} + (\alpha_E \frac{\partial p_I}{\partial \tau_E} + \alpha_I \frac{\partial p_E}{\partial \tau_E})T - \alpha_E m \frac{\partial T}{\partial \tau_E}$$

on welfare in *E* of increasing the production tax on non-renewable electricity is ambiguous because  $\delta b_E / \delta \tau_E < 0$ ,  $\delta p_i / \delta \tau_E > 0$  and  $\delta T / \delta \tau_E < 0$ , but strictly positive for  $m \ge 0$  and  $\tau_E$ small, but positive. For m = 0, the deviation from the social optimum to  $\phi_I > 0$  and  $\tau_E > 0$ imply a downward distortion in transmission:  $\delta T / \delta \phi_I < 0$  and  $\delta T / \delta \tau_E < 0$  yield  $T < T^*$ .

#### **Proof of Proposition 4**

Summarize the domestic welfare effects to get the aggregate welfare effect

$$\phi_I \frac{\partial q_I}{\partial m} + \tau_E \frac{\partial b_E}{\partial m} - m \frac{\partial T}{\partial m}$$

By straightforward differentiation of the first-order conditions (3) and (4):

$$\begin{aligned} \frac{\partial q_I}{\partial m} &= -\Upsilon \frac{D_I'}{c_T''} \left( \frac{1}{h_E''} - D_E' \right) > 0, \\ \frac{\partial b_E}{\partial m} &= \frac{\Upsilon}{h_E'' c_T''} \left( \frac{1}{h_I''} - D_I' \right) > 0, \\ \frac{\partial T}{\partial m} &= \Upsilon \frac{1}{c_T''} \left( \frac{1}{h_I''} - D_I' \right) \left( \frac{1}{h_E''} - D_E' \right) > 0. \end{aligned}$$

Hence, it is socially optimal to raise *m* above zero if  $\phi_I > 0$  and  $\tau_E > 0$ .

#### **Proof of Proposition 5**

To analyze the effects of certificate market integration, consider the homotopy  $ya + (1 - y)a_i$ , where  $a_i$  is the equilibrium certificate price under autarky implicitly defined by (1) and (2), a is the equilibrium certificate price under integration defined by the first-order

conditions in (1), the market clearing condition for non-renewable electricity in (2), all modified by  $a_I = a_E = a$ , plus the aggregate renewable electricity market clearing condition

$$g_I + g_E = f_I D_I (p_I + f_I a) + f_E D_E (p_E + f_E a).$$

The parameter  $y \in [0,1]$  is a measure of market integration where y = 1 refers to integration and y = 0 represents autarky. In this case (i = I, E):

$$p_i + ya + (1 - y)a_i = c'_i(g_i), p_i = h'_i(b_i), p_I - p_E = c'_T(T)$$

plus the market-clearing condition

$$b_i + g_i = D_i(p_i + ya + (1 - y)a_i) + (-1)^{\frac{i-E}{I-E}}T$$

define the equilibrium allocations  $(g_I, g_E, b_I, b_E)$ , wholesale prices  $(p_I, p_E)$  and transmission capacity *T* as functions of certificate market integration *y*. Differentiation yields

$$T'(y) = \Psi[(\frac{1}{c_E''} - D_E')(\frac{1}{h_I''} + \frac{1}{c_I''} - D_I')(a - a_E) + (\frac{1}{c_I''} - D_I')(\frac{1}{h_E''} + \frac{1}{c_E''} - D_E')(a_I - a)],$$

where

$$\Psi^{-1} = c_T^{\prime\prime} (\frac{1}{h_I^{\prime\prime}} + \frac{1}{c_I^{\prime\prime}} - D_I^{\prime}) (\frac{1}{h_E^{\prime\prime}} + \frac{1}{c_E^{\prime\prime}} - D_E^{\prime}) + \frac{1}{h_I^{\prime\prime}} + \frac{1}{c_I^{\prime\prime}} - D_I^{\prime} + \frac{1}{h_E^{\prime\prime}} + \frac{1}{c_E^{\prime\prime}} - D_E^{\prime} > 0.$$

Certificate market integration thus boosts transmission investment (T'(y) > 0) if the exporting country has a comparative advantage  $(a_E < a < a_I)$  in the production of renewable electricity but lowers investment (T'(y) < 0) if the importing country has the comparative advantage  $(a_I < a < a_E)$ .

Consider the welfare effects. Define quasi-surplus

$$\widetilde{w}_{i}(y) = v_{i}(p_{i} + f_{i}y(a - a_{i}) + f_{i}a_{i}) + (p_{i} + y(a - a_{i}) + a_{i})g_{i} - c_{i}(g_{i}) + p_{i}b_{i}$$
$$-h_{i}(b_{i}) + \alpha_{i}[(p_{I} - p_{E})T - c_{T}(T)]$$

as a function of market integration y. Utilize the first-order and market-clearing conditions:

$$\widetilde{w}_{i}'(y) = (g_{i} - f_{i}q_{i})(a - a_{i}) + (-1)^{\frac{i - E}{I - E}}(\alpha_{I}p_{E}'(y) + \alpha_{E}p_{I}'(y))T_{i}$$

Summarizing over countries yields

$$\widetilde{w}'(y) = (g_i - f_i q_i)(a - a_i) + (f_j q_j - g_j)(a_j - a).$$

To move further, the following comparative statics result will be useful:

$$\frac{dp_i}{dy} = \Psi[(\frac{1}{c_j''} - f_j D_j')(a_j - a) - c_T''(\frac{1}{h_j''} + \frac{1}{c_j''} - D_j' + \frac{1}{c_T''})(\frac{1}{c_i''} - f_i D_i')(a - a_i)]$$

After some tedious, but straightforward arithmetic:

$$\frac{dg_i}{dy} - f_i \frac{dq_i}{dy} = (\frac{1}{c_i''} - f_i D_i') \frac{dp_i}{dy} + (\frac{1}{c_i''} - f_i^2 D_i')(a - a_i)$$

$$= \Psi(\frac{1}{c_{i'}'} - f_{I}D_{I}')(\frac{1}{c_{E}''} - f_{E}D_{E}')(a_{j} - a) + \Psi(\frac{1}{c_{i'}'} - f_{i}^{2}D_{i}')(\frac{1}{h_{j'}'} + \frac{1}{c_{j'}'} - D_{j}')(a - a_{i})$$
$$+ \Psi(\frac{1}{h_{i'}'c_{i'}'} - \frac{f_{i}^{2}D_{i}'}{h_{i'}'} - \frac{(1 - f_{i})^{2}D_{i}'}{c_{i'}'})[1 + c_{T}''(\frac{1}{h_{j'}'} + \frac{1}{c_{j'}'} - D_{j}')](a - a_{i}).$$

The above expression is strictly positive by the assumption that  $a_i \le a \le a_j$  with at least one strict inequality. Hence,  $g_i(y) - f_i q_i(y) > g_i(0) - f_i q_i(0) = 0$  for all y > 0. By the same token,  $g_j(y) - f_j q_j(y) < 0$  for all y > 0 owing to  $g'_j(y) < f_j q'_j(y)$ . Hence,  $\tilde{w}'(y) > 0$  and surplus therefore strictly higher under certificate market integration than autarky.

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